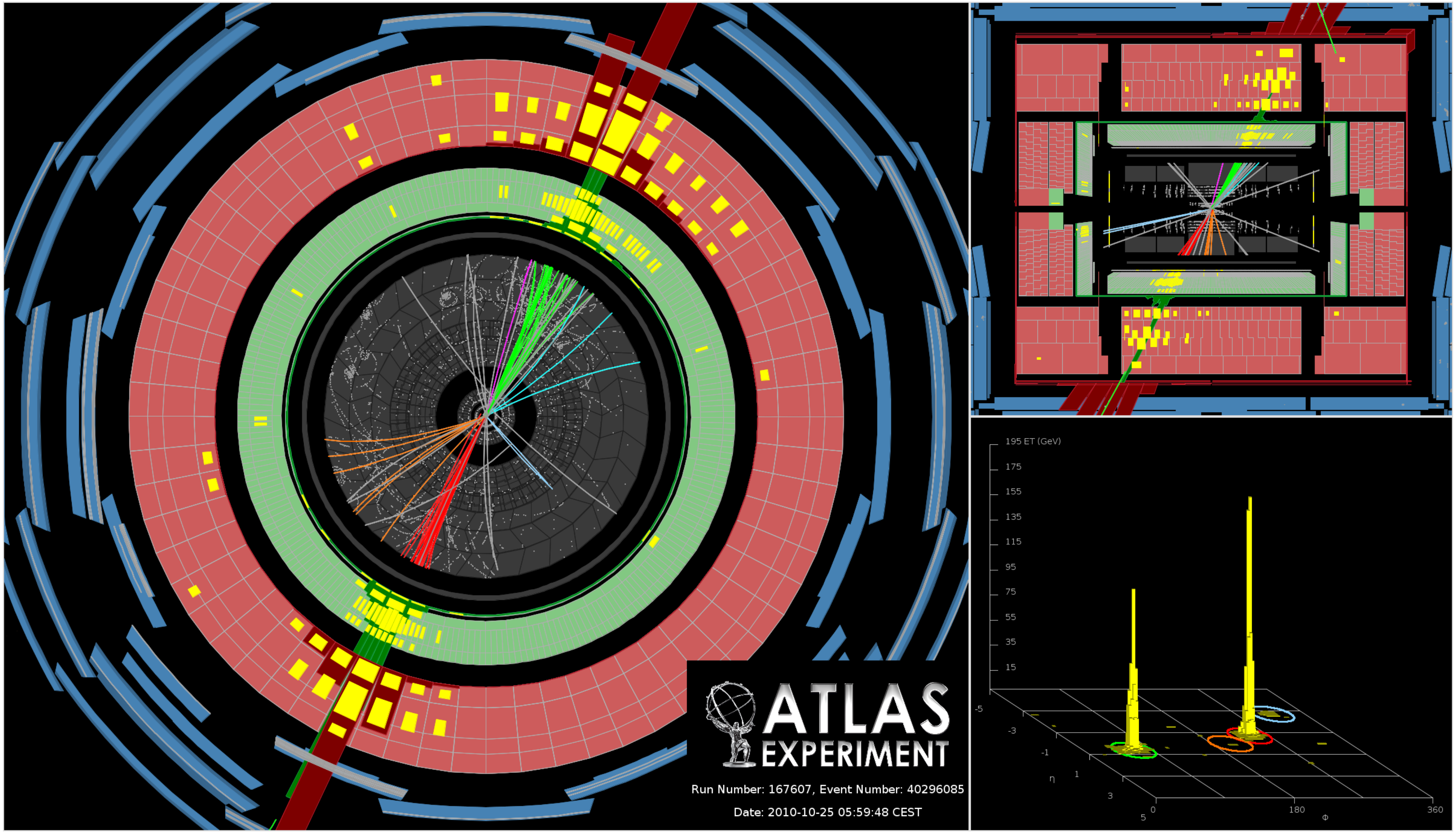
Standard Model @ Hadron Colliders
IV. Hard QCD interactions - Jets

Hard interaction: Jets



Jets are universal

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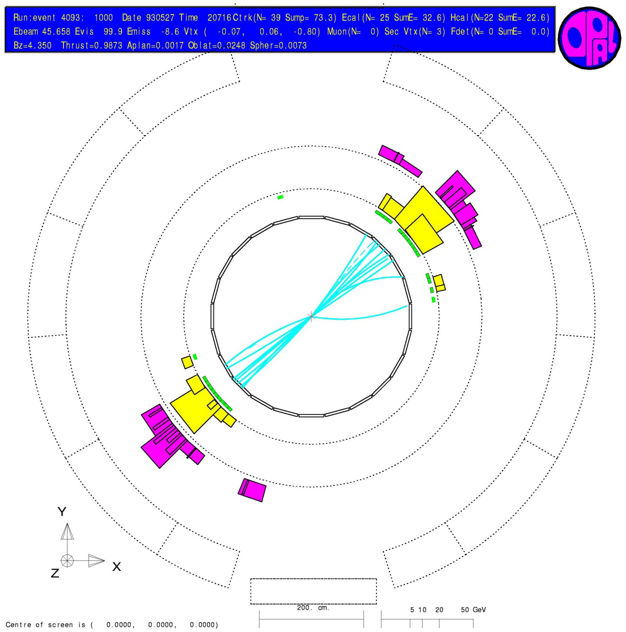
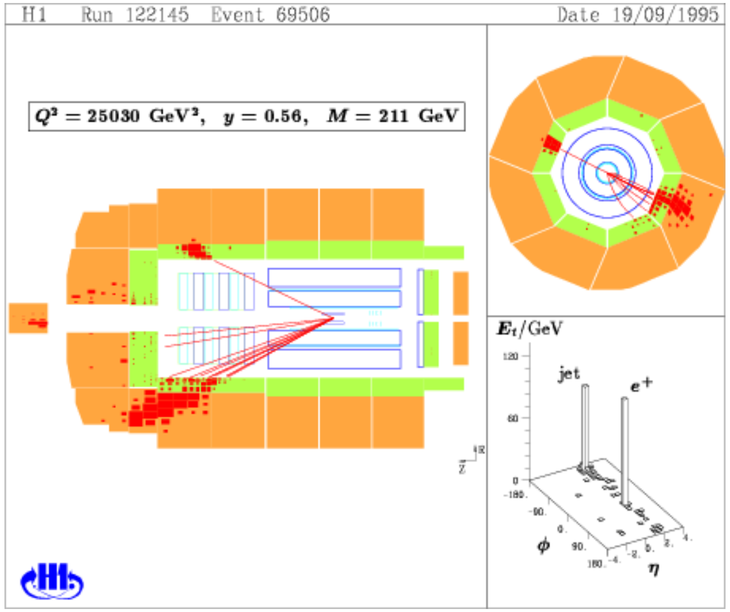
$e^+ e^-$ collisions



e p collisions



Jets: representative of quarks and gluons

- ➔ stringent test of theory
- ➔ experimenal challenge: extract partons from 1000 hadrons
- ➔ experimentally attainable
  direction and energy + (sometimes) parton flavour

How to find a jet ?

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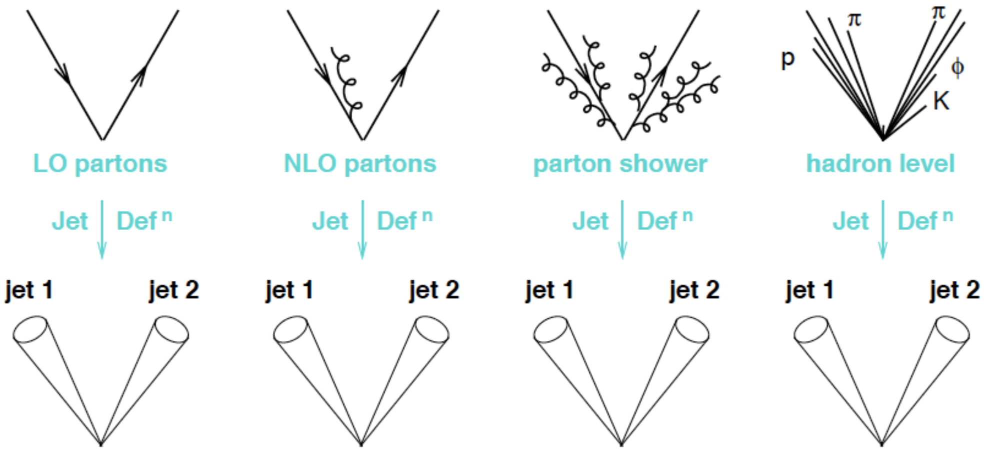
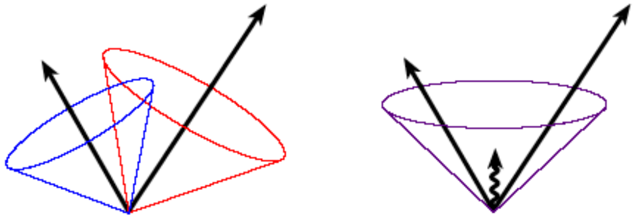
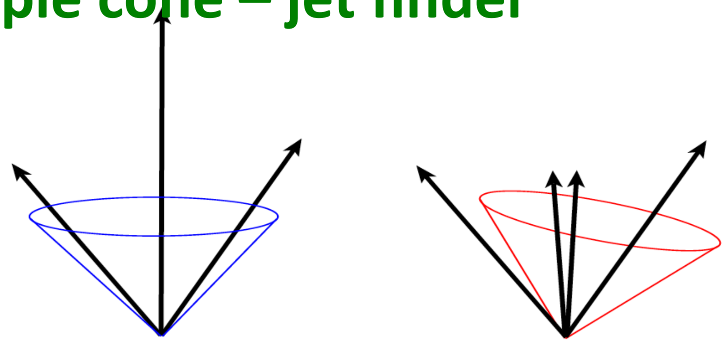


Unambiguous connection to underlying partons ➔ Comparison to theory

‚collinear', ‚infrared' safe

Not so straight – forward: example cone – jet finder





Low momentum ‚infrared' particle changes jets

Two ‚collinear' particles change jets

Sequential jet finder

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‚Reverse evolution of event'

1 Select one particle (e.g. most energetic)
2 Find ‚most similar' particle, (e.g. smallest angle, p_t)
3 Is combination smaller than predefined ‚cut off' value (e.g. maximum angle, maximum mass ....)

IF YES:

4 Combine to a new ‚pseudo – particle' (e.g. sum 4 – momenta)
5 Go to 2

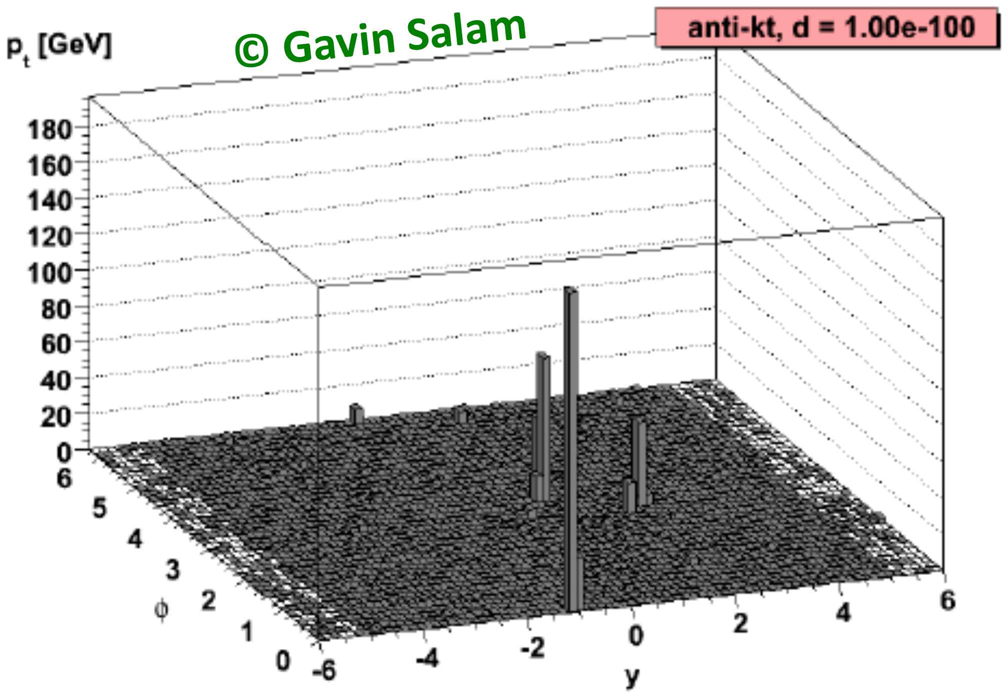
IF NO:

4 Jet found: sum of all associated particles

Favoured jet finding at LHC: ‚Anti – kt‘

$$\mathbf{d_{ij} = \min(p_{ti}^{-2}, p_{tj}^{-2}) \frac{\Delta R_{ij}^2}{R^2}}$$

$$\mathbf{\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2}$$



Infrared + collinear safe

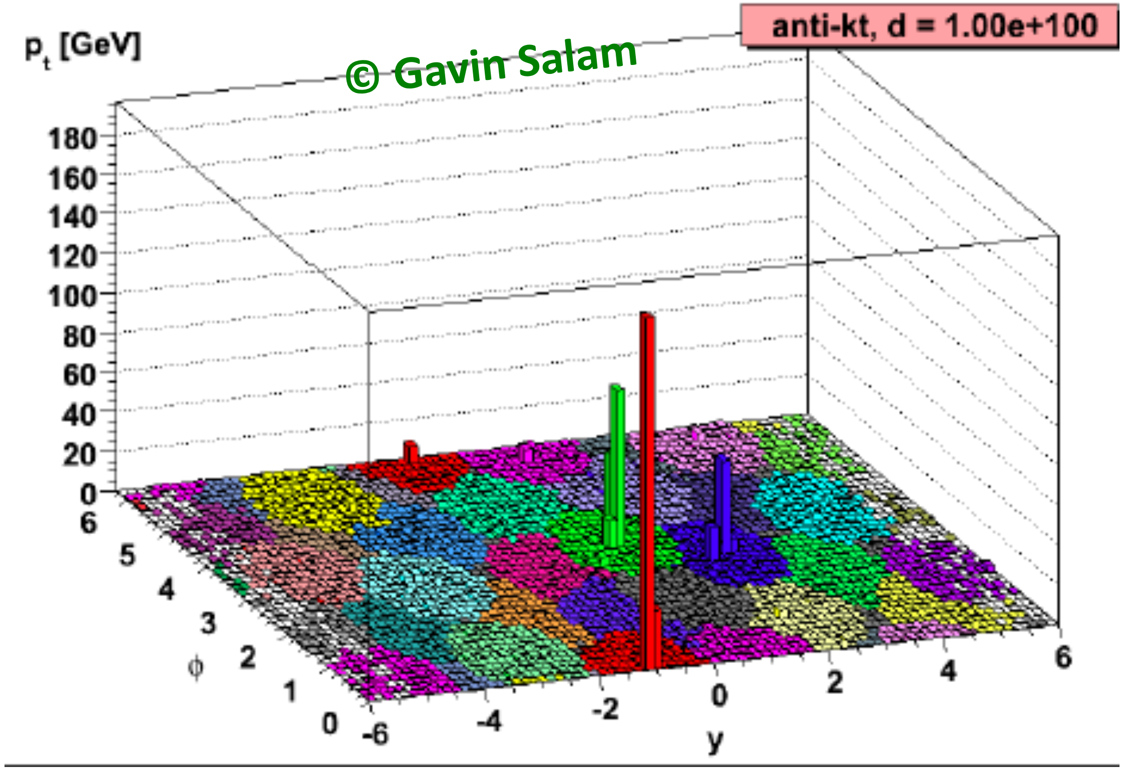
hard particles: seeds‘ for jets: favoured by min(p_t^2)

separated in space are disctinct seeds: large ΔR_{ij}

Low p_t, close by particles assigned to seeds

Only particles within predefined R considered

The final jets



All particles assigned to jets

Close to circular in space
Simplifies experimental corrections
(retains features of cone algorithm)

Note: special treatment of particles close to beam

In a nutshell:

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Hard process
= (data
- pile up events from simultaneous pp – collisions
- underlying event from proton remnants)
x (transfer from jets → partons)
x (unfolding of parton energies = parton distribution fct.)

Involved,
.... but with experimental knowledge feasible

Measurement of jet cross section

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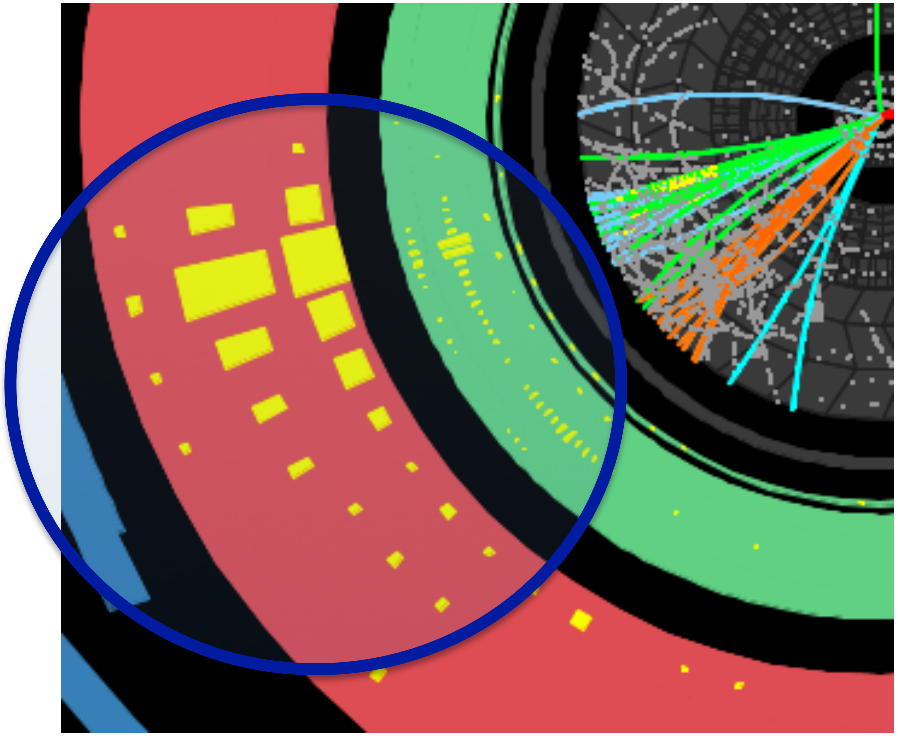
What we learn

- Theoretical calculations @ NLO
- Test of QCD at highest available energies
- Sensitivity to pdfs
- Sensitivity to BSM physics

What we need

- Jet energy reconstruction
- Good understanding of Jet Energy Scale (JES)
- Good understanding of Jet Energy Resolution (JER)

How to measure jets: just calorimeter



Sum up adjacent charge depositions in electromagnetic and hadronic calorimeter

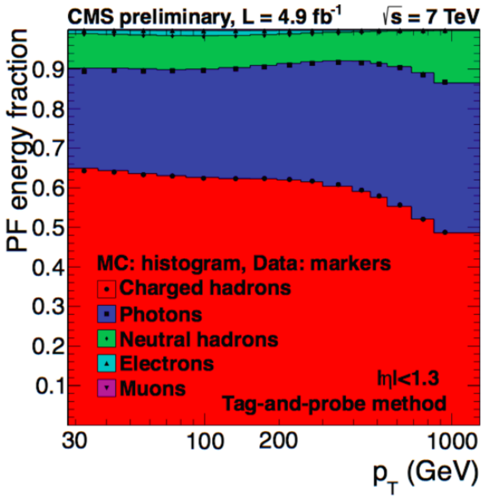
- deposition just proportional to energy (e/π ~1)
- beware of spread due to magnetic field
- Good segmentation: correct for em/had energy deposition

N.B.: missing transverse energy from ALL clusters

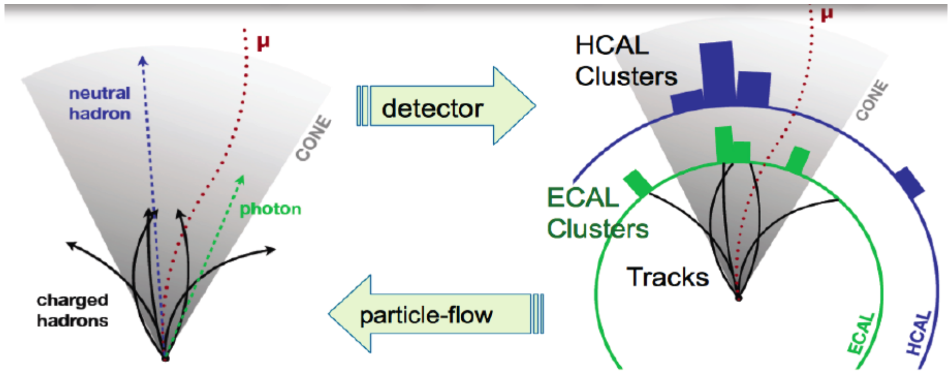
$$P_{x,miss} = -\sum_i p_{x,i}, \quad P_{y,miss} = -\sum_i p_{y,i}$$

$$E_{T,miss} = \sqrt{P^2_{x,miss} + P^2_{y,miss}}$$

How to measure jets: energy flow



50 – 60% of energy in charged particles
higher resolution in tracking detector



Use tracking info:
energy, impact in calorimeter
Subtract energy from calo dep.

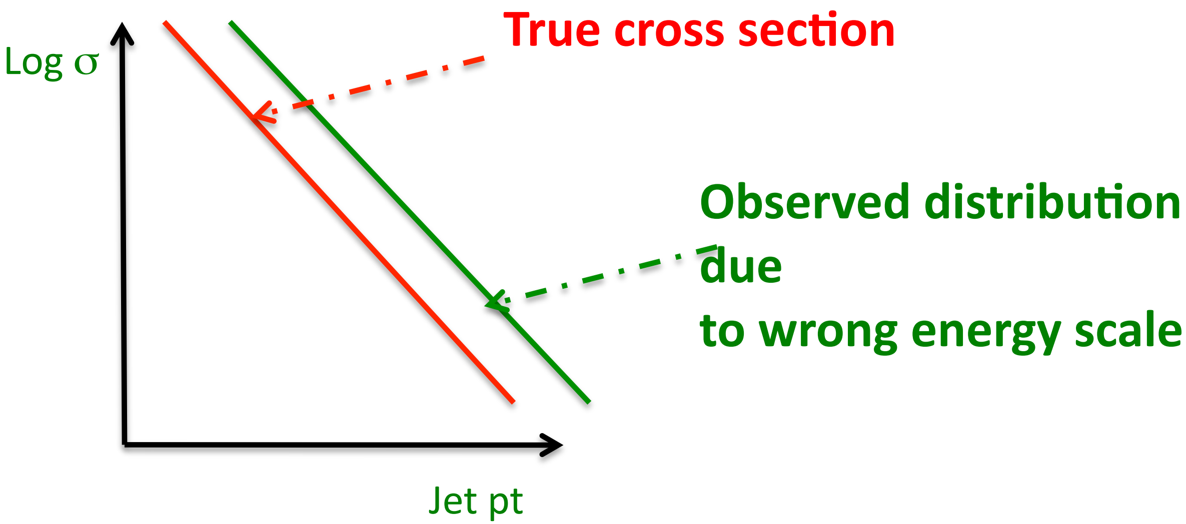
- Requires very good lateral (and longitudinal) granularity
- Depends on quality of Inner Tracker vs. Calorimete reco
- In pile – up events: identify energy from hard interaction

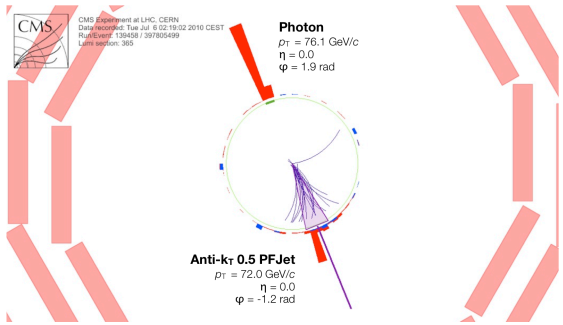
The experimental challenge I

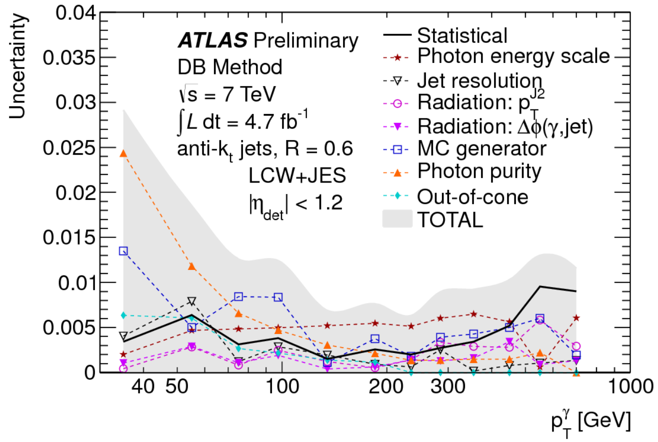
Steeply falling cross section ➔ sensitivity to energy scale

Jet energy determined from calorimeter (+ tracking information)

Sophisticated calibration procedure







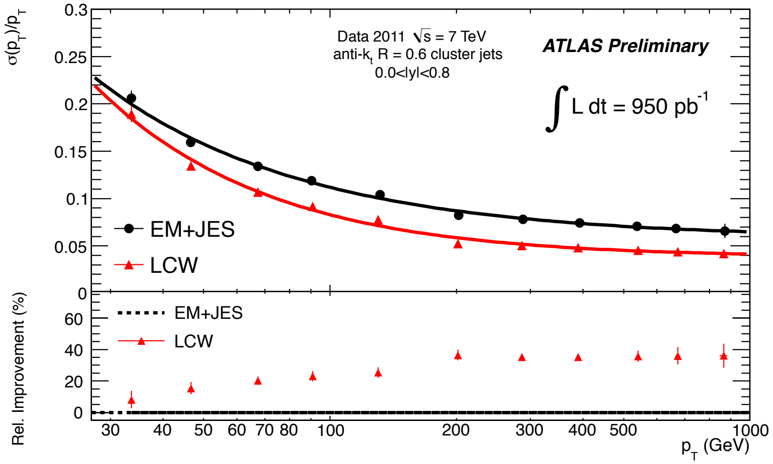
Use γ + jet events:
Jet energy scale known to 1 – 3%!

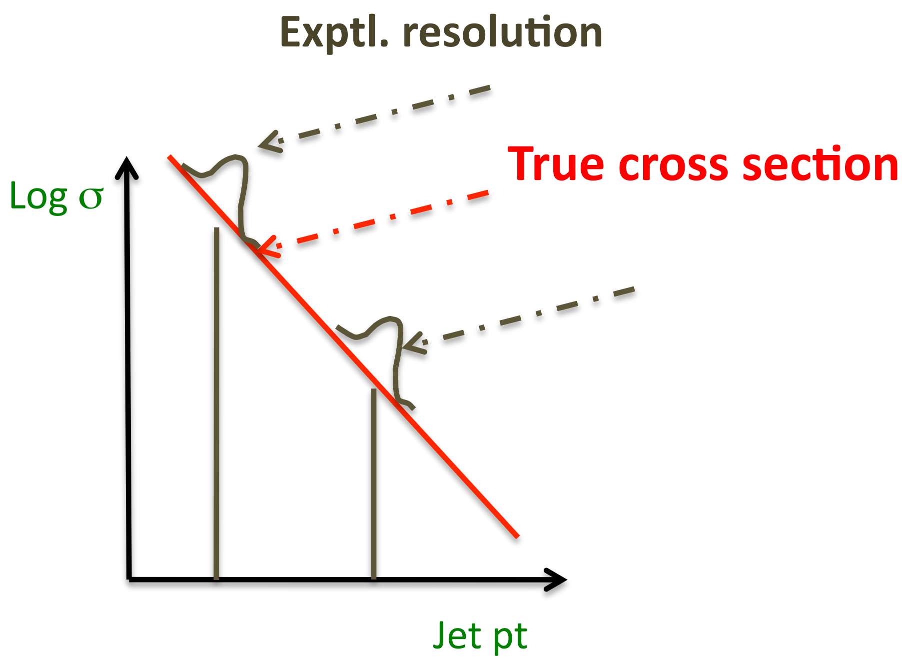
The experimental challenge II

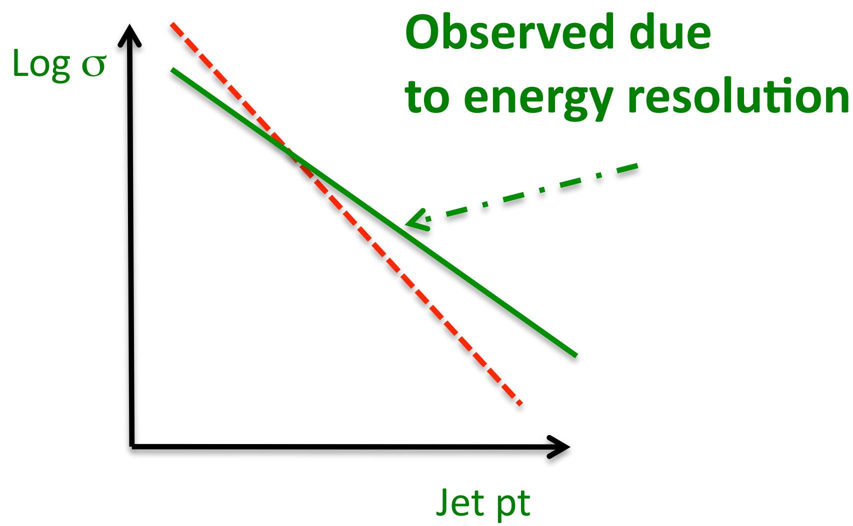
sensitivity to energy resolution

compare p_T balance in data to simulation with known JER:

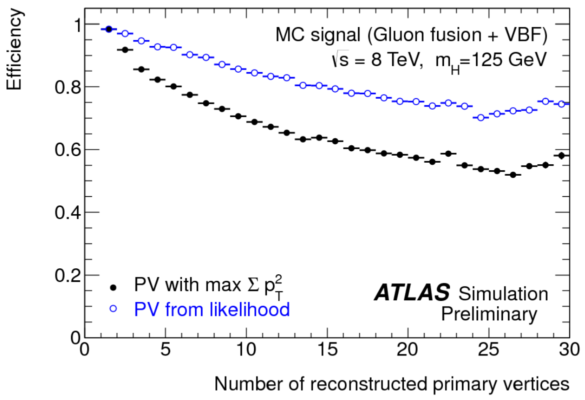
ok to some 14%



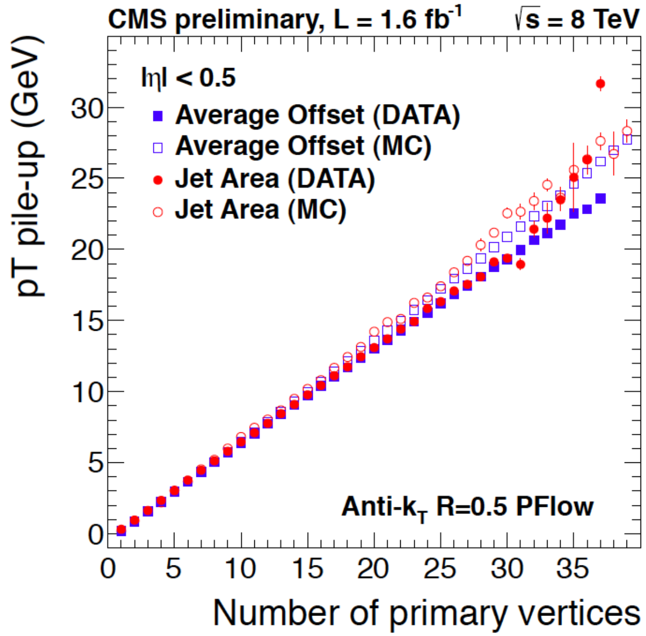


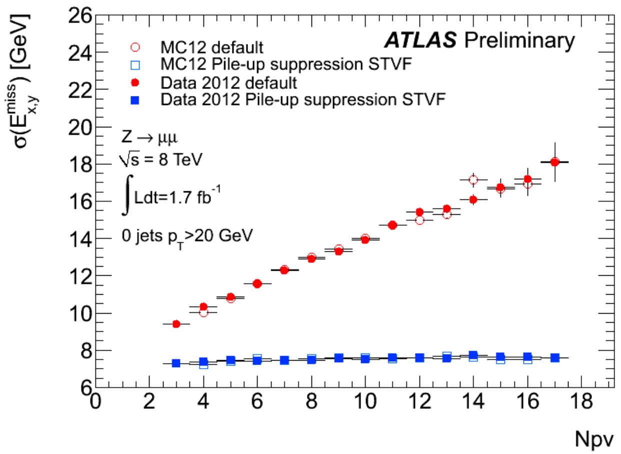


Distortions due to pile - up



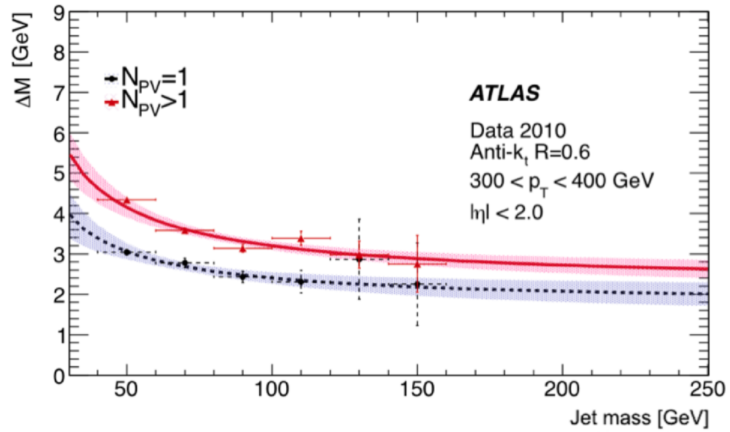
Identifying the ‚correct' vertex position





Reconstructed missing energy

Jet mass

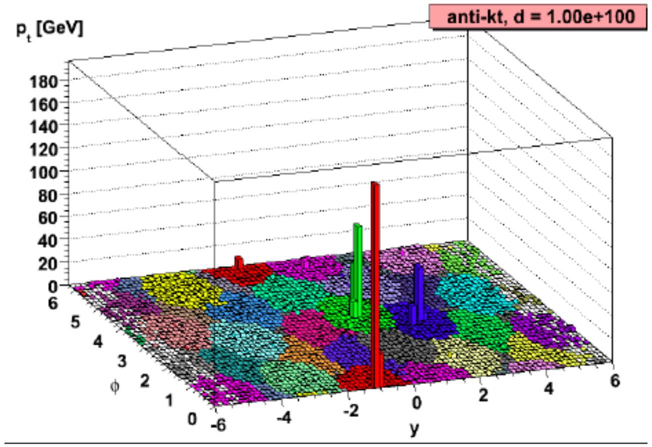


Experimental challenge!
New algorithms/methods needed

Jet area method

Principle:

- ➢ per event average deposited energy/ΔR outside jets: ρ
- ➢ subtract from jet E = A*ρ

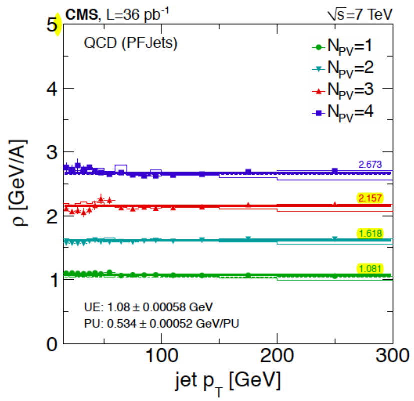


Needed: jet area A!

Anti k_T : not quite circular

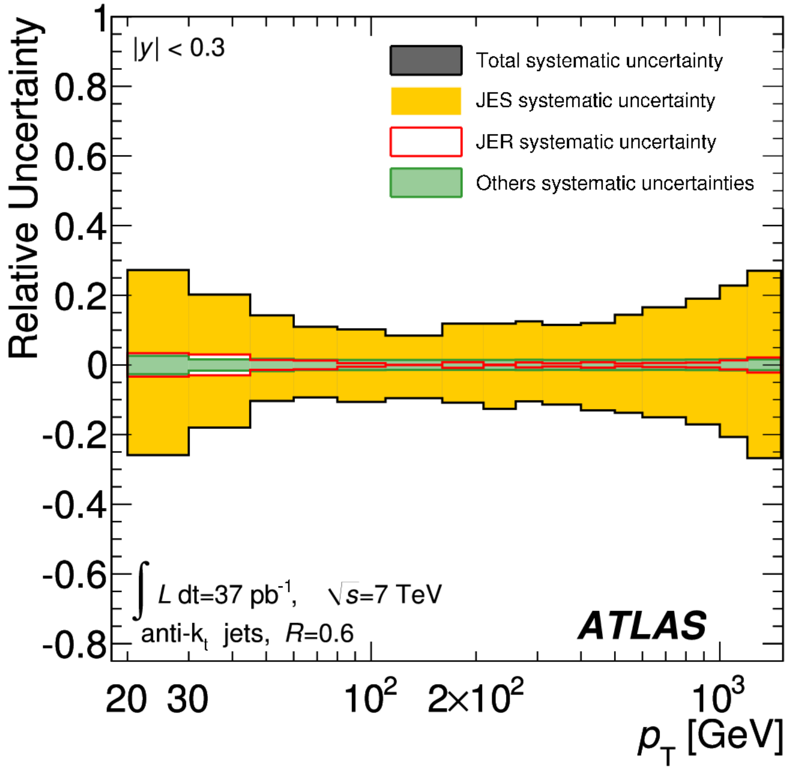
➔add very many ‚infitely' low p particles and perform clustering

➔ Exact shape (and area) given



Correction of ~ 0.5 GeV/pile up (R=0.5)

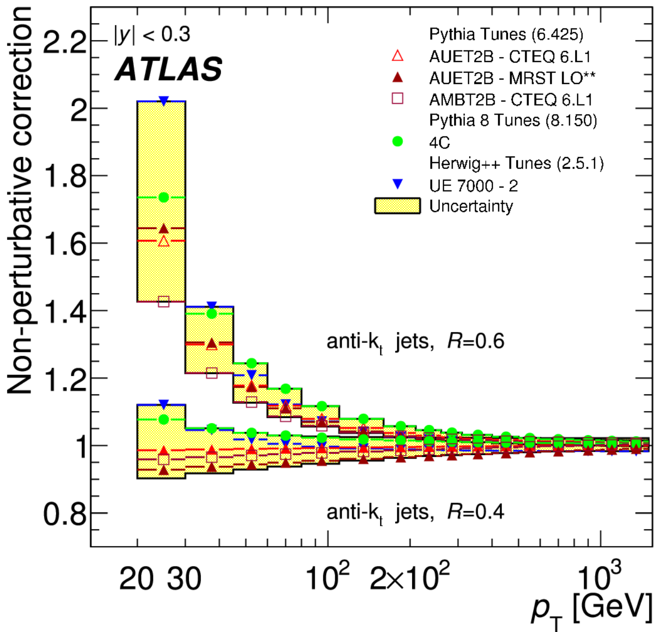
Uncertainties: summary



Experimental uncertainties dominate at low p_T

Note: loss of control of uncertainties for p_T < 20 GeV

Conversion to ‚truth‘ level



Sizeable corrections depending on R

Increasing at low p_T

Reconstructed Jet ➔ ‚hadron level‘

➔Comparison to theory requires
matrix element + hadronisation
Uncertainty from hadronisation models, but can be tested

Reconstructed Jet ➔ parton

➔Direct comparison to theory possible
Uncertainty from models how parton ➔ hadrons
‚Belief‘ in models

Jet cross sections in rapidity and pT

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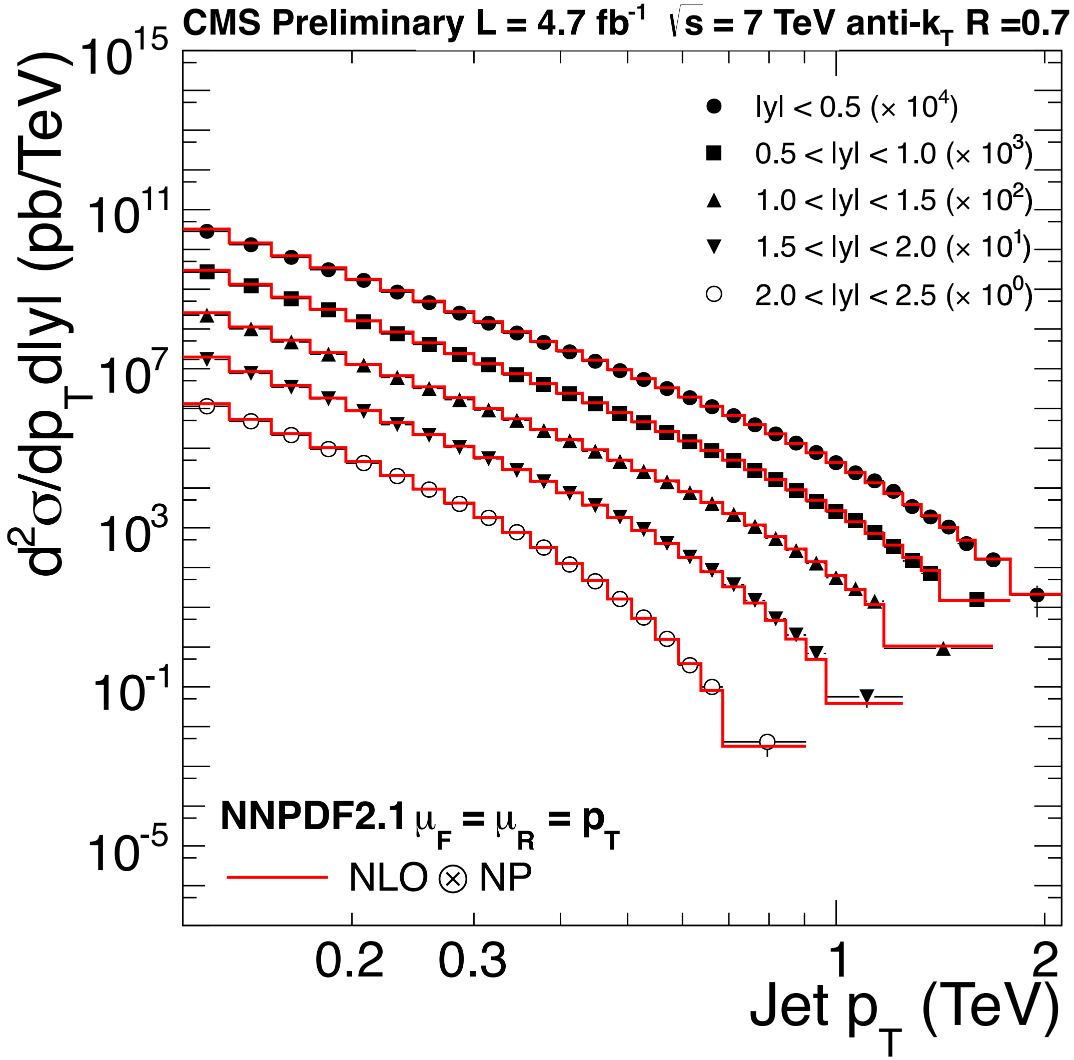

Excellent agreement theory <-> data over huge phase space

QCD ok for jets of 2 TeV

jet – jet mass

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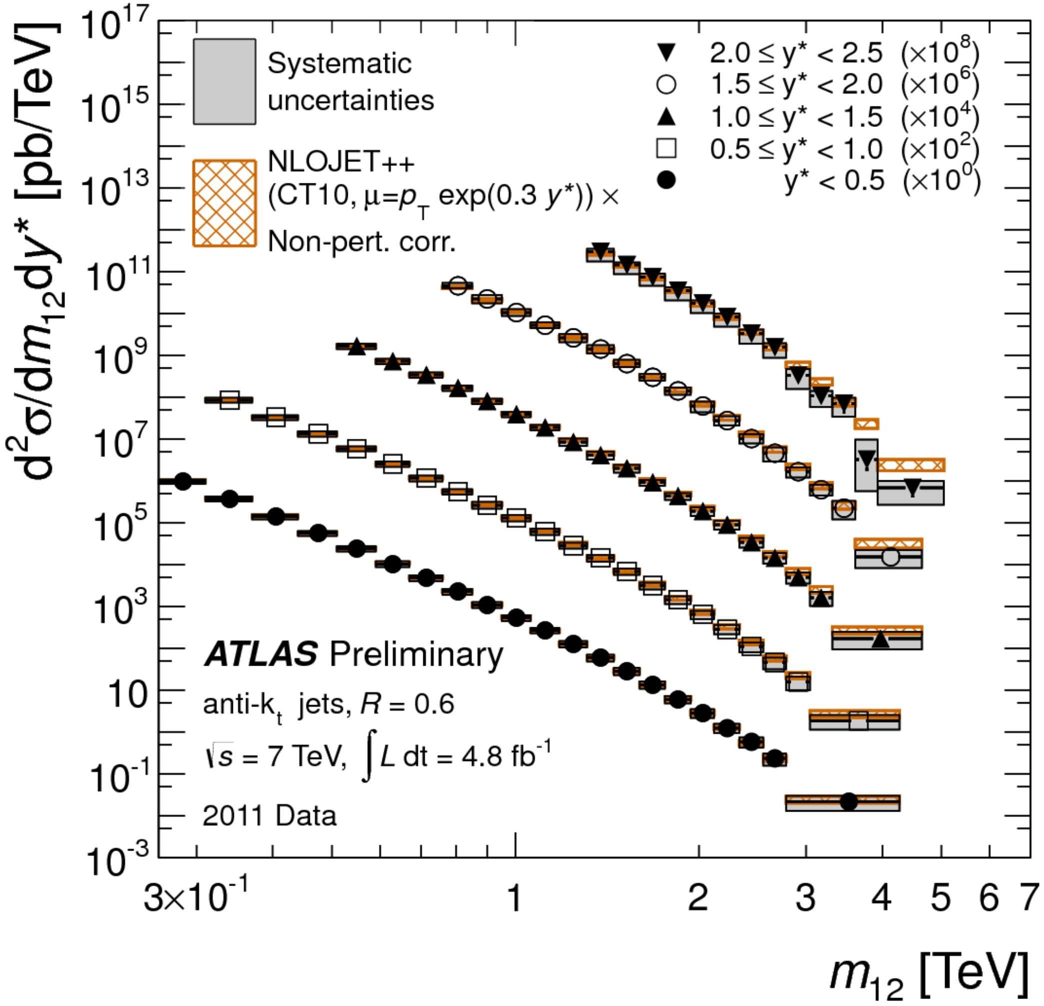

Excellent agreement theory <-> data

Probing masses up to 5 TeV!

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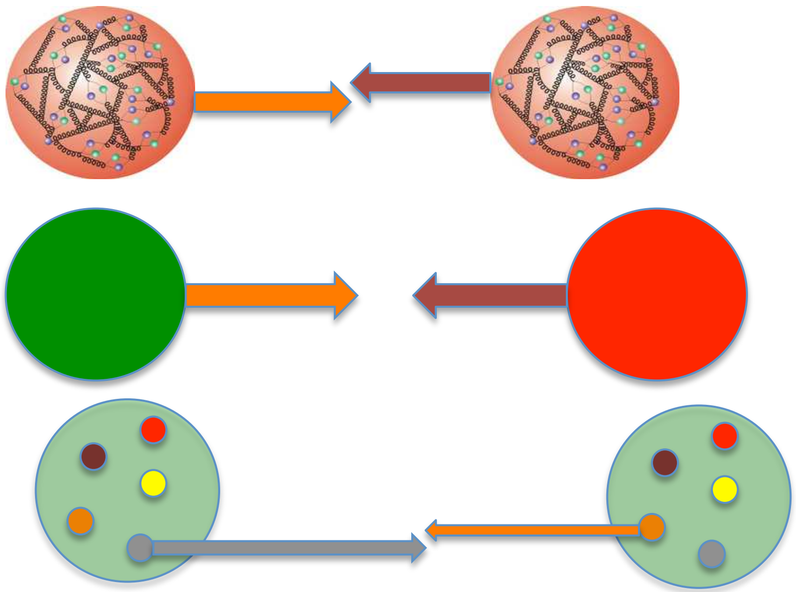
Probing high pT – jets = search for BSM: Are partons composite?



pp – interaction

qq – interaction

interaction of quark constituents ????

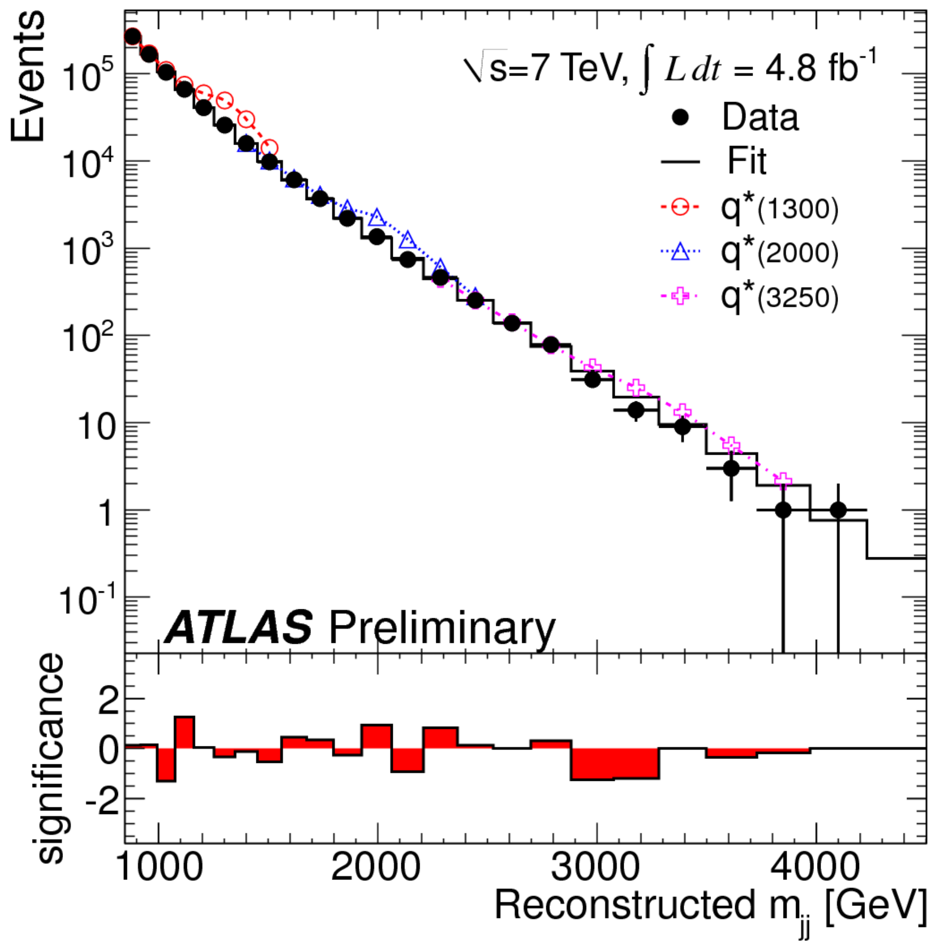
Convention: parametrize via ‚contact interaction‘

➔ interference SM + ‚new interaction‘ at mass Λ

$$\mathcal{L}_{CI} = \frac{g^2}{\mathbf{\Lambda^2}} \eta_{LL} (\bar{\psi}_L \gamma^\mu \psi_L)(\bar{\psi}_L \gamma_\mu \psi_L) + (RR, LR)$$

$$\sigma_{ff} = | \mathcal{M}_{SM} |^2 + \mathbf{2} \frac{\mathbf{1}}{\mathbf{\Lambda^2}} \mathcal{RE}(\mathcal{M}_{\mathbf{SM}} \cdot \mathcal{M}_{\mathbf{CI}}) + \frac{1}{\Lambda^4} | \mathcal{M}_{CI} |^2$$

Jets and BSM: Search for di – jet resonances



An excited quark ?

q^* ➔ q + g

(N.B: excited atom, nucleus ....)

Strong signal for compositeness

Search for dijet resonance

Limit:

q* mass > 3.66 TeV

Highest ATLAS Mjj 4.1 TeV

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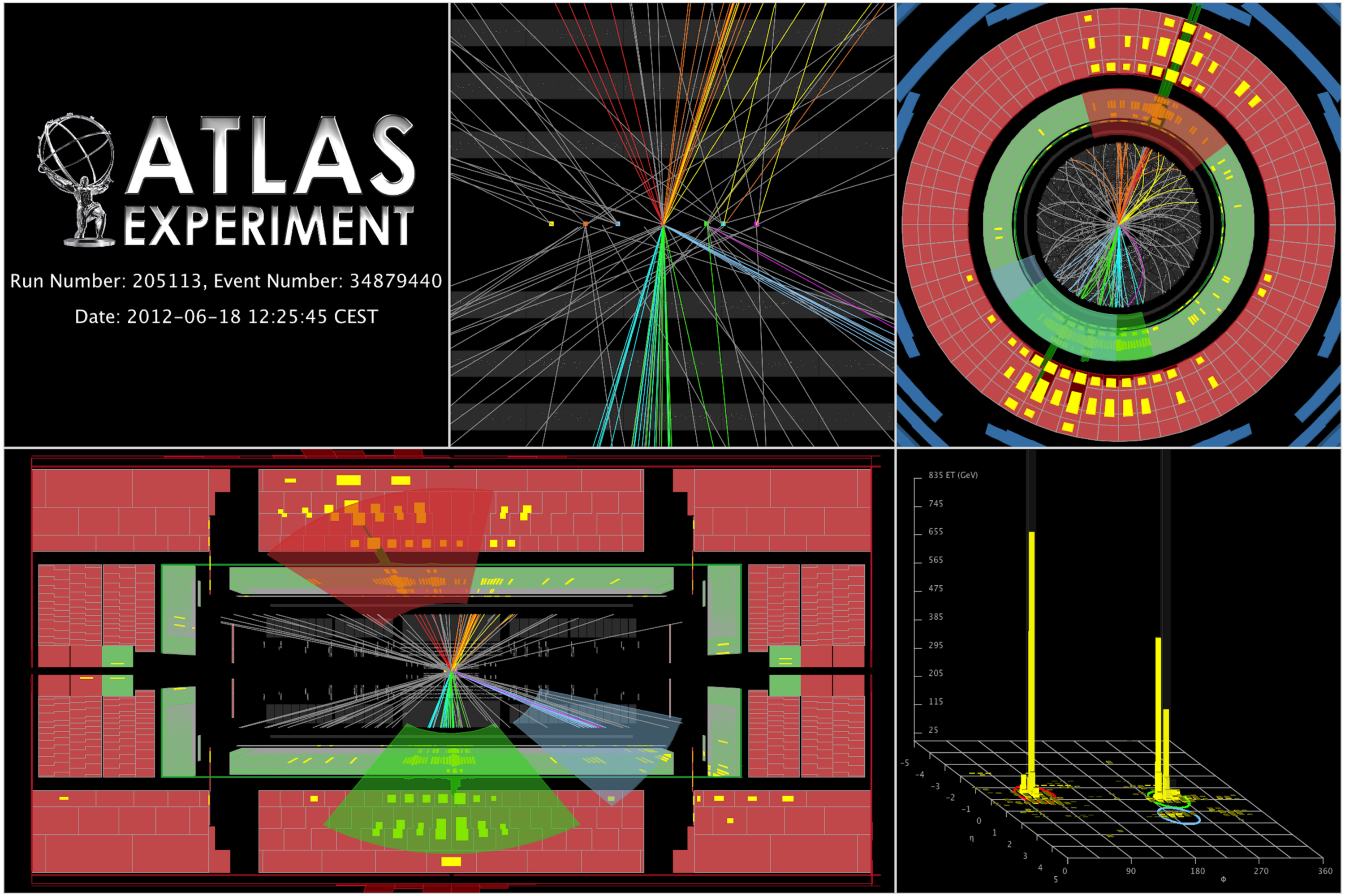

Higher sensitivity to compositenesss

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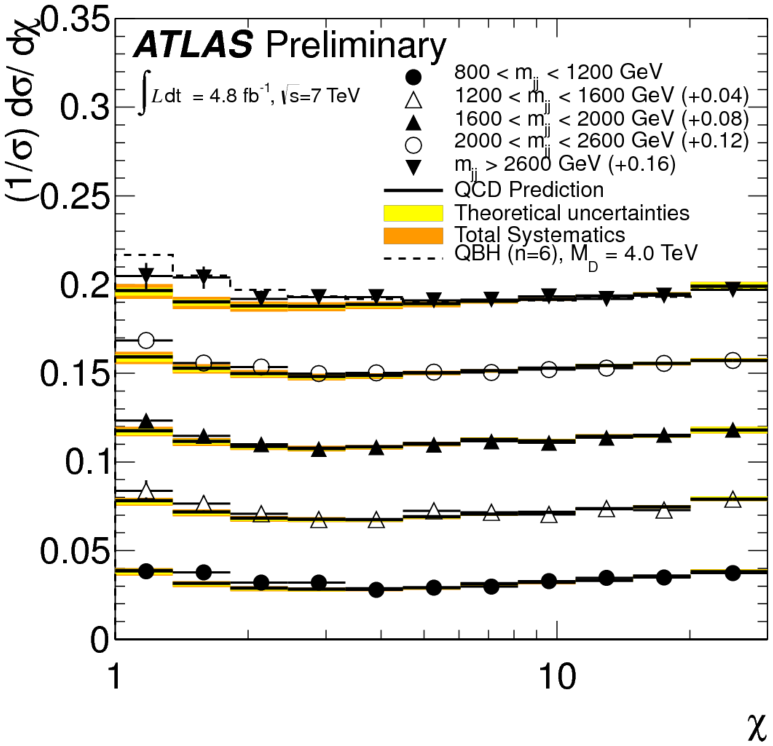

modified angular distribution: apparent in observable

$$\chi = e^{|y_1 - y_2|}$$

Note: difference of rapidities is Lorentz invariant

➔ $y^* = ½ (y_1 – y_2)$

Rapidity of each jet in cm system

y* represents decay angle

QCD: strongly peaked in θ ➔ flat in χ

New physics: ‚isotropic' in θ ➔ low χ

No deviation from SM observed: Λ_{CI} > 7.8 TeV

Note: results applicable to other exotic models: black – holes, colour octet quarks, ...

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Standard Model @ Hadron Colliders
V. Hard QCD – Structure of Jets

QCD effects: number of jets

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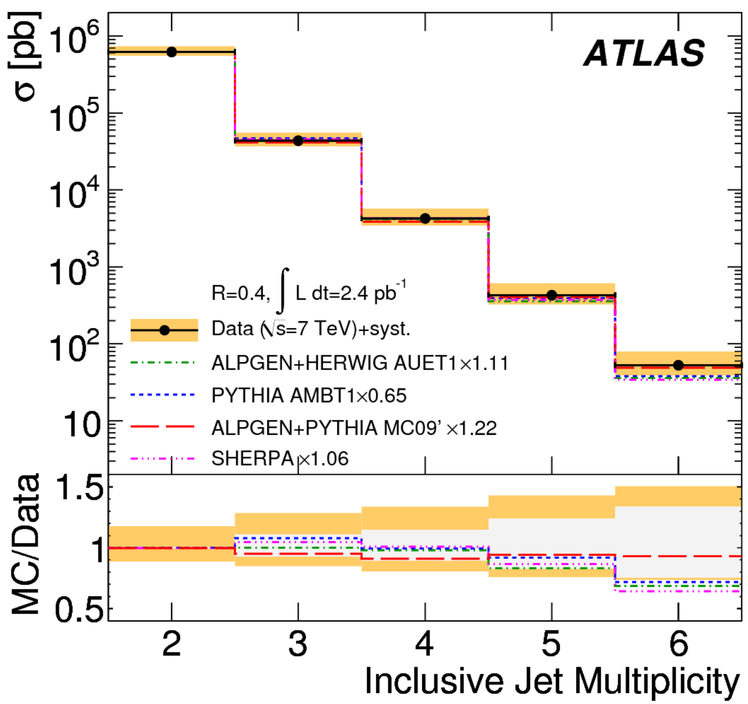
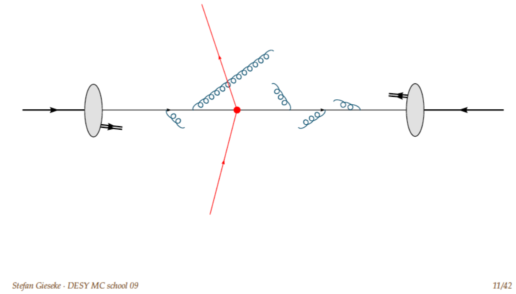
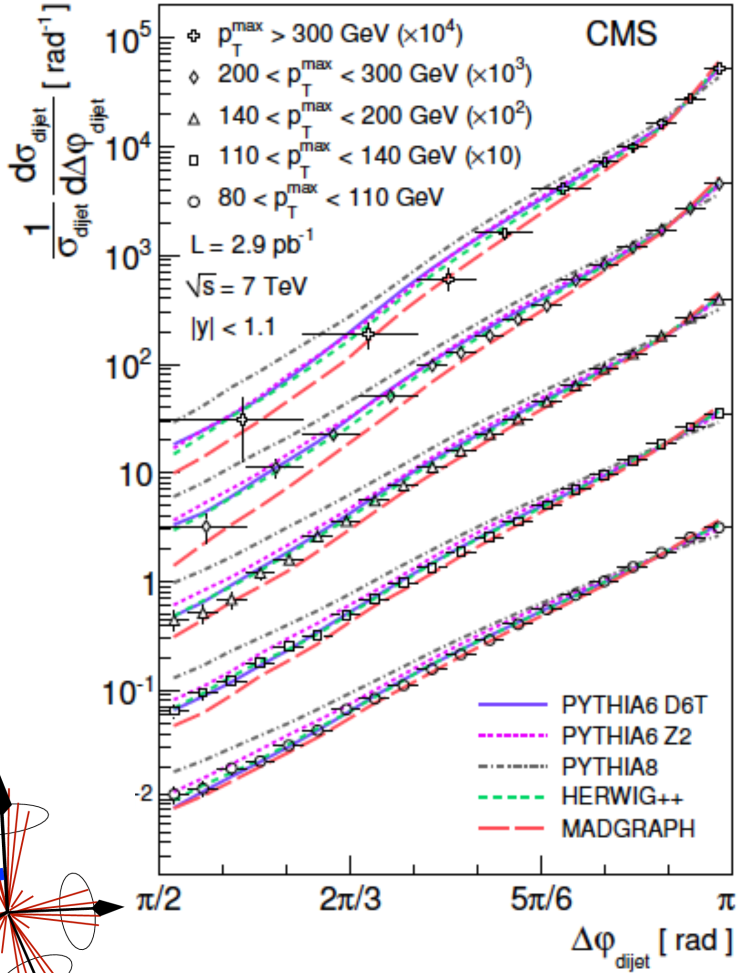


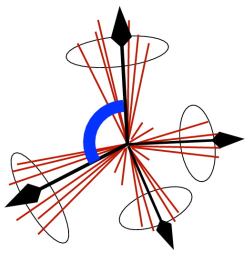


Calculations either full NLO
i.e. matrix element 2→3 (+shower)
or
LO matrix element 2→ n (+shower)

LO generators: good description of jet multiplicities

The effects of gluon radiation

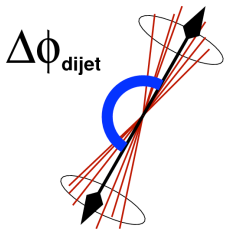




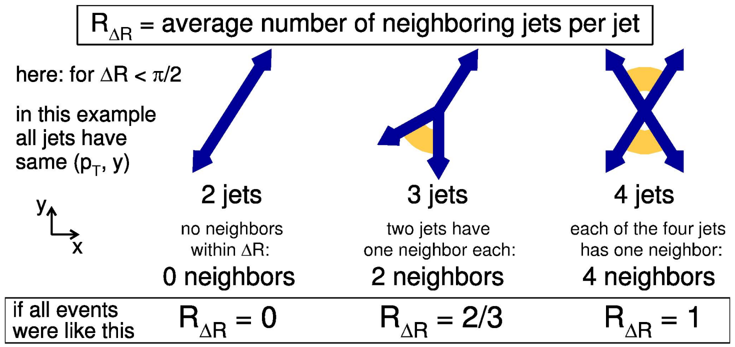
Additional jets affect momentum balance of two highest p_T jets

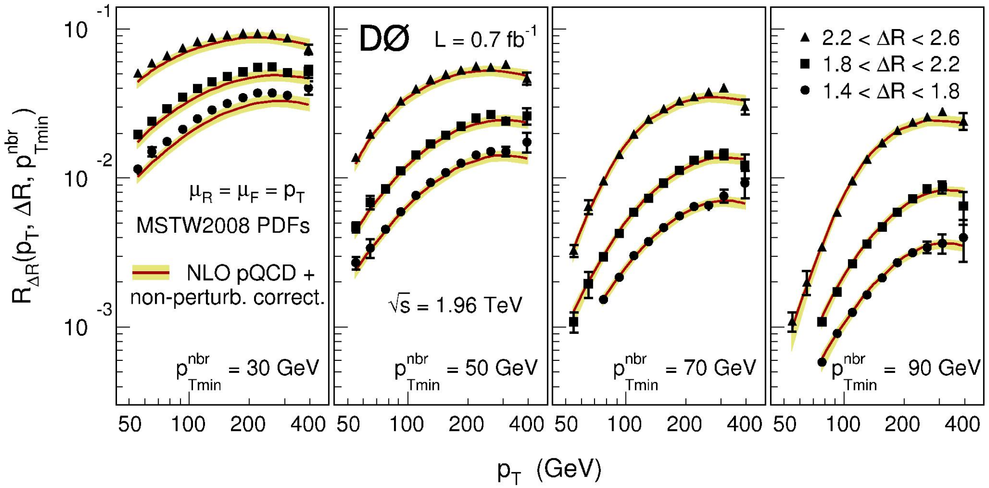
➔Azimuthal angle smaller

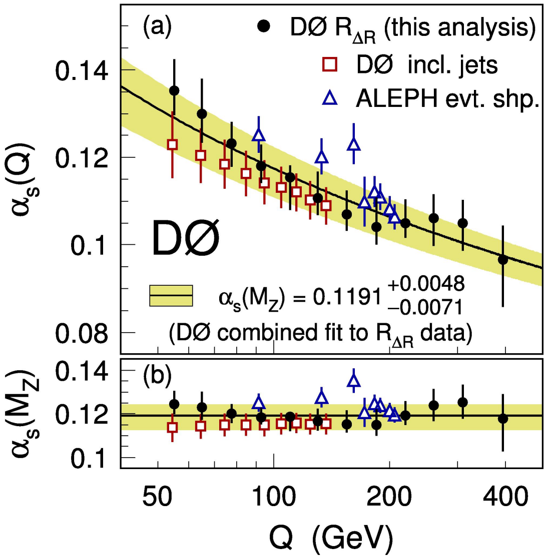
A measure for gluon radiation



A measure for α_s







A mixture of g→gg, q→qg

Consistent with α_s precision measurements

In itself marginal precision

High p_T Jets

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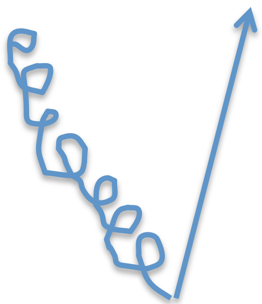
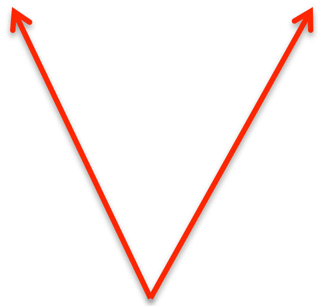
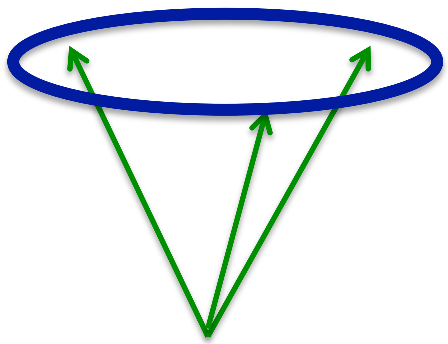
High p_T jets: important to explore TeV scale physics
May be due to boosted objects: top, higgs → substructure
Important: does QCD describe the structure of boosted jets?



Gluon radiation:
‚in plane',
Quark more energy than
gluon: ‚asymmetry'



2 – body decay of
heavy particle (‚Higgs')
‚in plane'
energy equally shared



n – body decay of
heavy particle (‚top')
‚out of plane'
energy equally shared

(a few) Observables

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Mass

$$M^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \tilde{p}_i\right)^2$$

Jet width: measure of concentration of jet energy along axis

Planar flow: measures if energy is spread in a plane

P = 0, in plane (decay X→A,B)

P→1, multiparticle jet

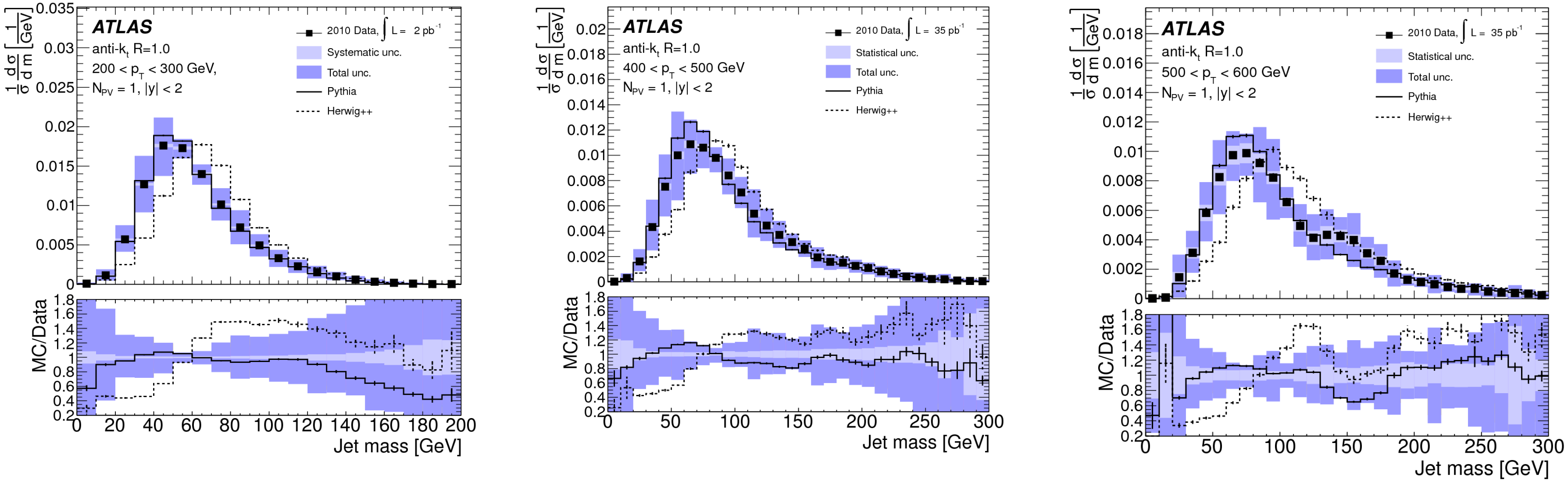
$$I_E^{kl} = \frac{1}{M}\sum_i \frac{1}{E_i} p_{i,k} p_{i,l}, \quad P = 4 \times \frac{\det(I_E)}{\mathrm{Tr}(I_E)^2}$$

Eccentricity: measure if jet profile a perfect circle

Angularity: symmetry of energy flow inside jet

$$\tau_a = \frac{1}{M}\sum_i E_i \sin^a\theta_i \left[1-\cos\theta_i\right]^{1-a} \text{ for } a = -2 \Longrightarrow \sim \frac{1}{M}\sum_i E_i \frac{\theta^6}{8\cdot\theta^2}$$

Jet mass in high pT Jets



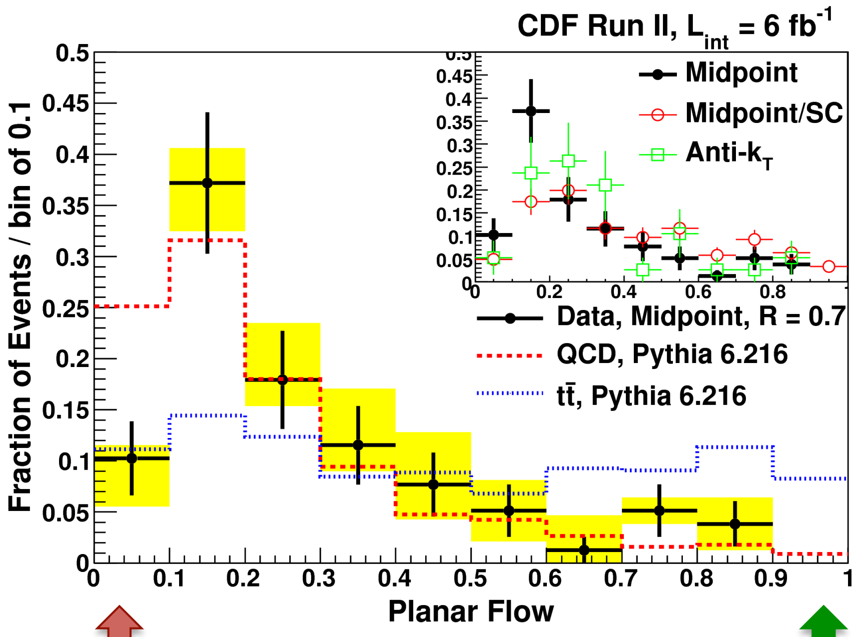
Mass increases with jet p_T:

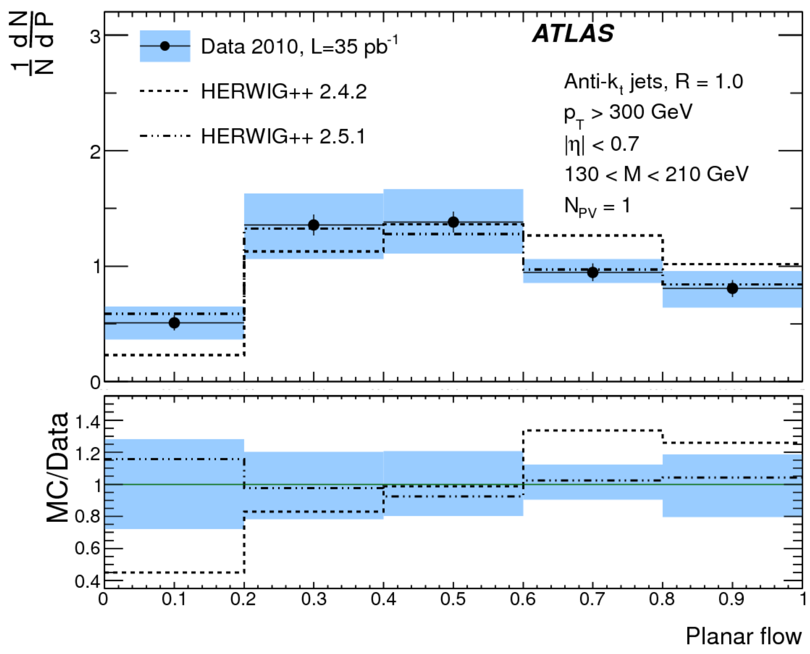
$$M_{jet} \propto \alpha_s(p_T) \cdot p_T \cdot \Delta R$$

Mass depends on ΔR and jet finder

Agreement with QCD calculations/models

Planar flow in high pT Jets





planar

circular

Most (high p_T) jet planar – agreement with QCD expectation

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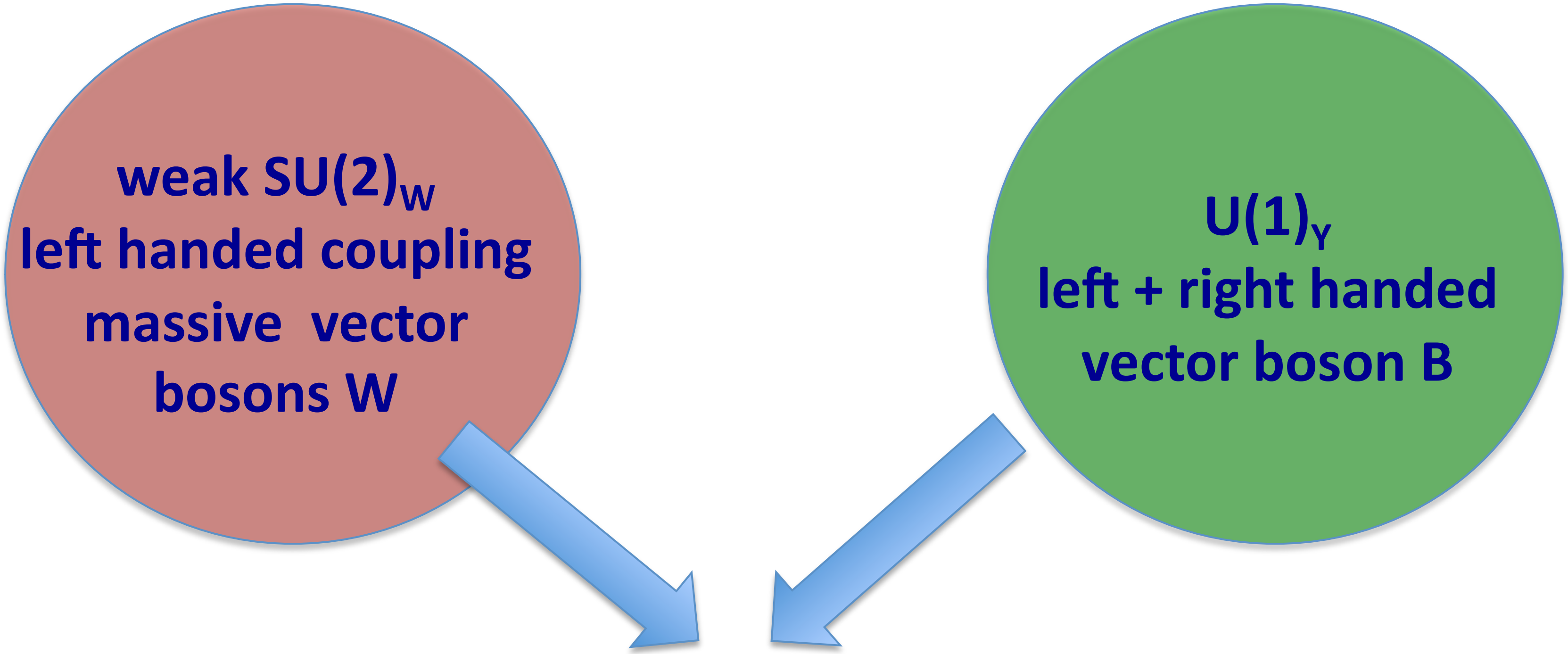
Standard Model @ Hadron Colliders
VI. W/Z + Jets

Electroweak facts



Interactions mix → physical particles γ, Z^0

$$\mathbf{A}_\mu = \mathbf{B}_\mu \cdot \cos\theta_\mathbf{w} + \mathbf{W}^\mathbf{3}_\mu \cdot \sin\theta_\mathbf{w}$$

$$\mathbf{Z}_\mu = -\mathbf{B}_\mu \cdot \sin\theta_\mathbf{w} + \mathbf{W}^\mathbf{3}_\mu \cdot \cos\theta_\mathbf{w}$$

Electroweak facts II

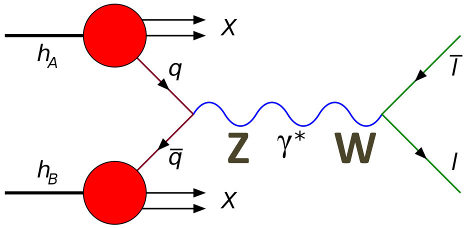
Unambiguous predictions of all measurements in terms of mass of Z^0 boson or mixing angle θ_w

$$\begin{aligned} \alpha_{em} &= 1/137.03599976(50) \\ G_\mu &= 1.16639(1) \cdot 10^{-5} \quad \mathrm{GeV}^{-2} \\ M_Z &= 91.1882(22) \quad \mathrm{GeV} \end{aligned}$$

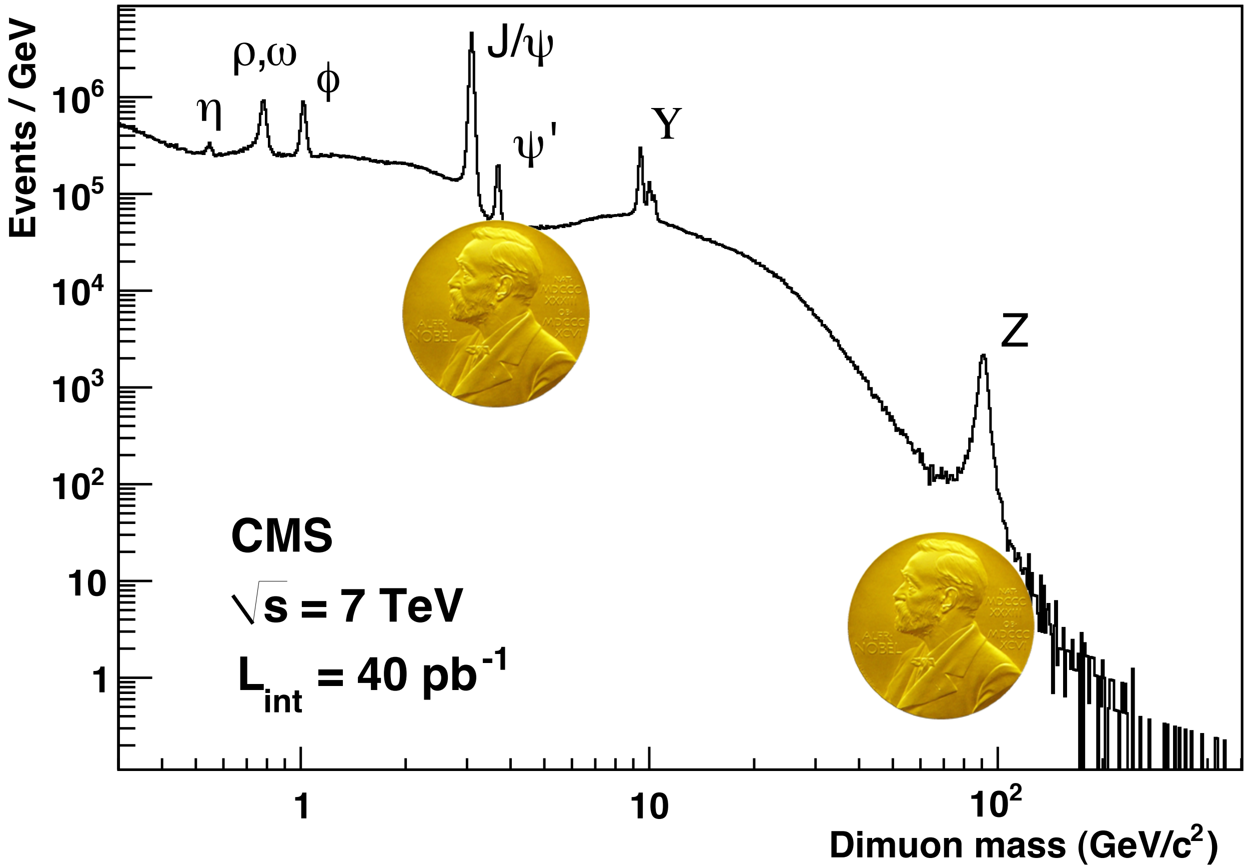
Can all measurements be consistently explained with these?

- ➔ **NO! Sensitive to Quantum fluctuation of unknown (top – quark and) Higgs boson**
- ➔ **Hadron collider contribution: M_W, M_{top}, M_{Higgs}**

Key process: Drell - Yan



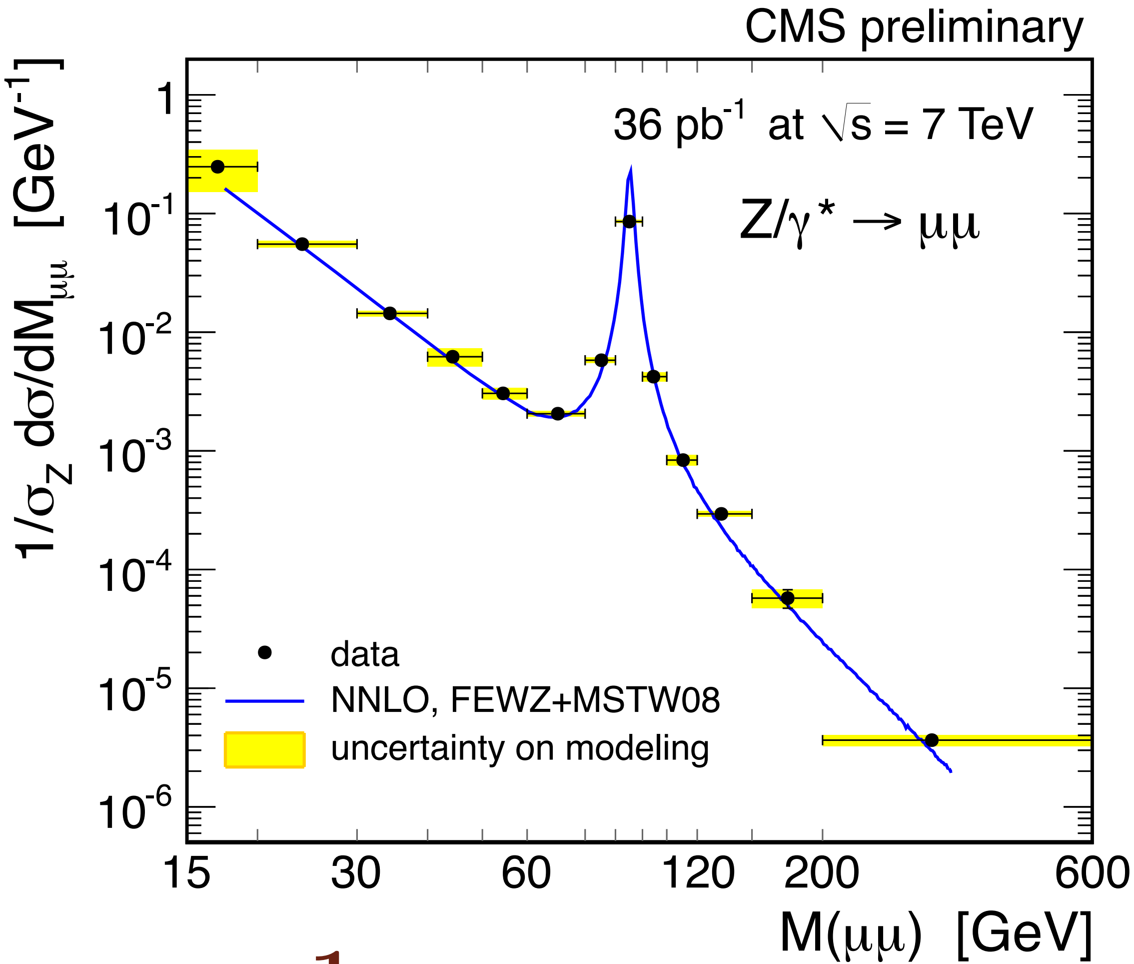
Crucial process in history of Standard Model



Rapidly falling X-section

Note:
previous distribution summary of several triggers

X-sec steeply falling



$$\sigma_{\mathbf{DY}} \propto \frac{\mathbf{1}}{\mathbf{M^2}} \times \mathcal{L}_{\mathbf{q\bar{q}}} \times \mathrm{Resonance}$$

LEP: precision meassurement of M_Z

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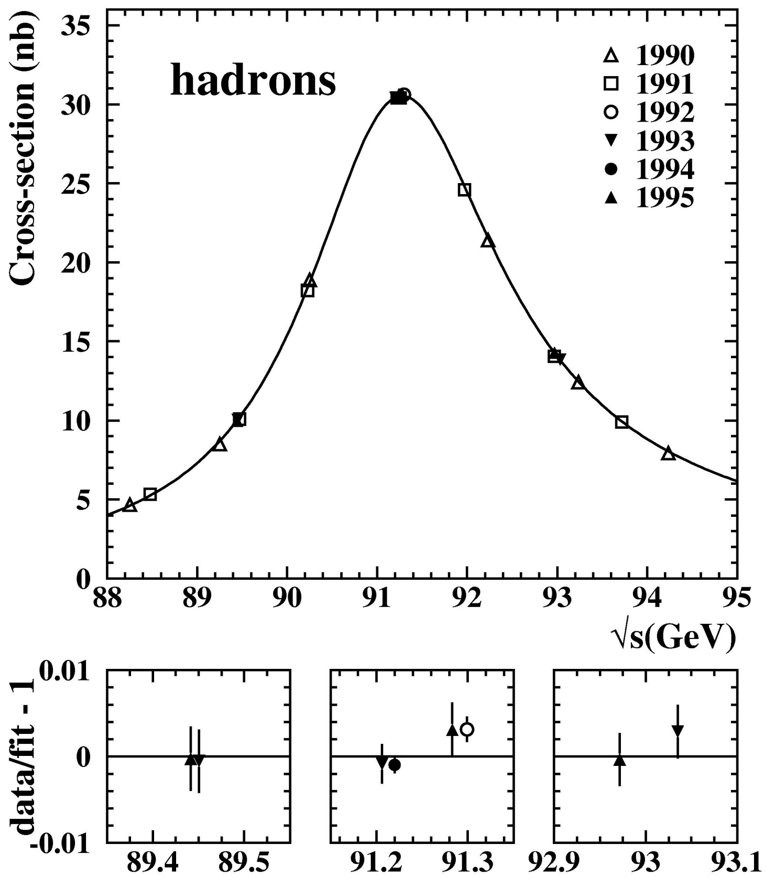

Precise knowledge of beam energy:
- **Moon tides**
- **water level in Jura**
- **TGV schedule**

and precise measurement of event yield:
- **full acceptance of decays**
- **exact luminosity**

and precise theoretical calculations:
- **HO corrections resonance shape**
- **HO corrections Bhabha scattering**

$$M_Z = 91.1822\ (22)\ \text{GeV}$$

Decays of the W/Z^0

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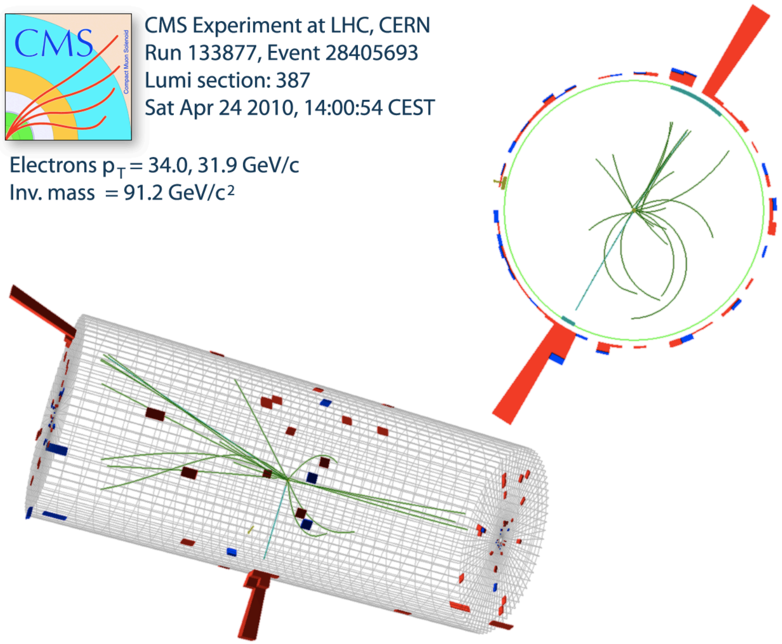
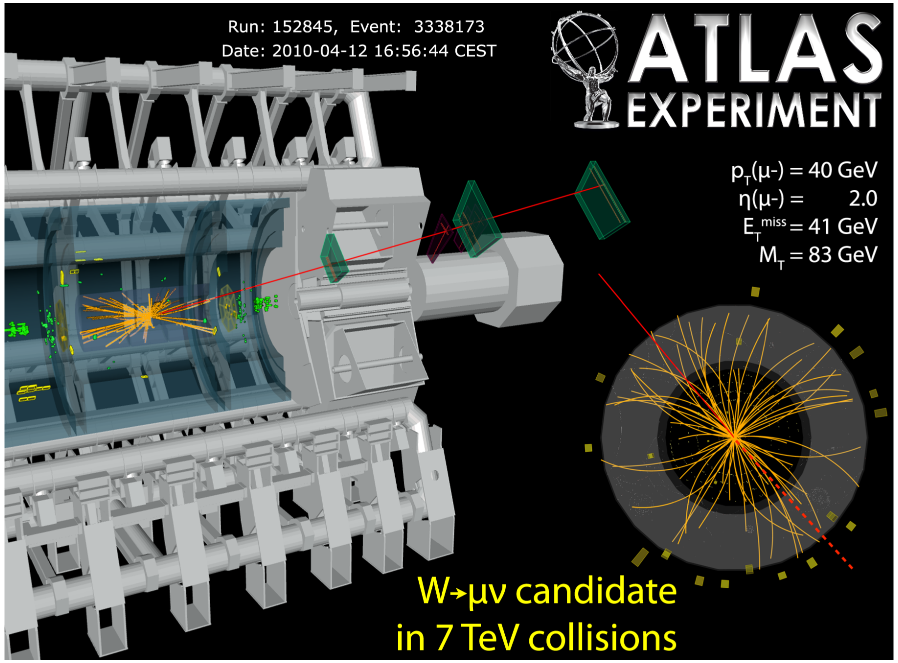
In general: W, Z decay into e, μ, τ, ν and quarks

Experimentally most visible @ LHC: decays into e, μ





Branching ratios of

2*3% and **2*11%**

Z^0 reconstruction at the LHC

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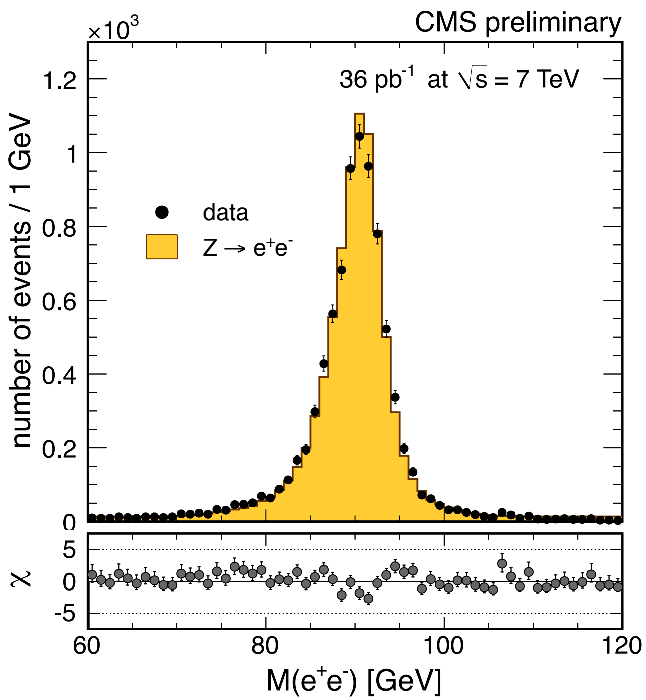

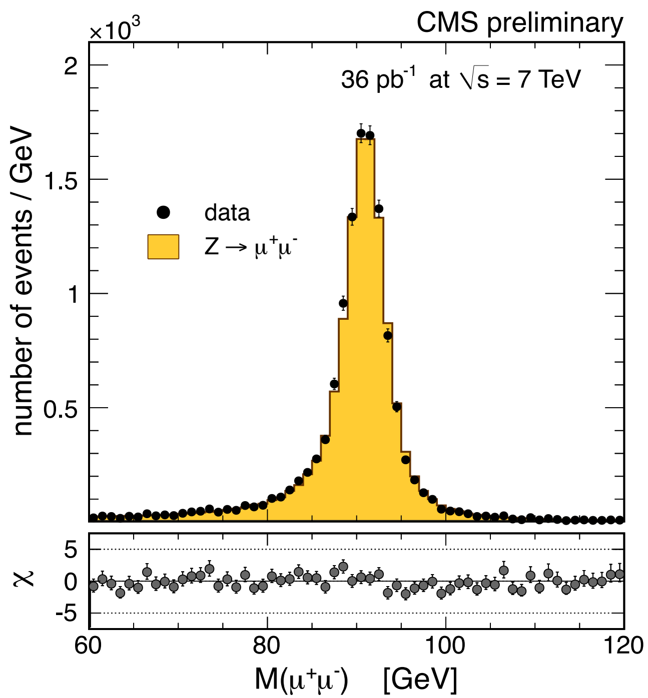

A clear, almost background – free signal

1 fb^{-1} mean some 1 million Z^0s

A lot of physics!

A lot for detectors: calibration of electromagnetic calorimeter

W reconstruction at the LHC

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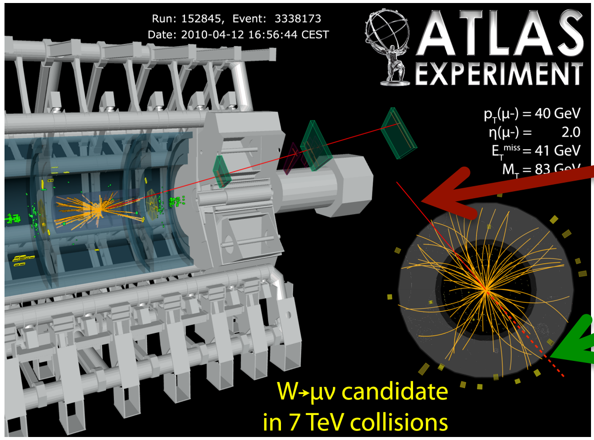
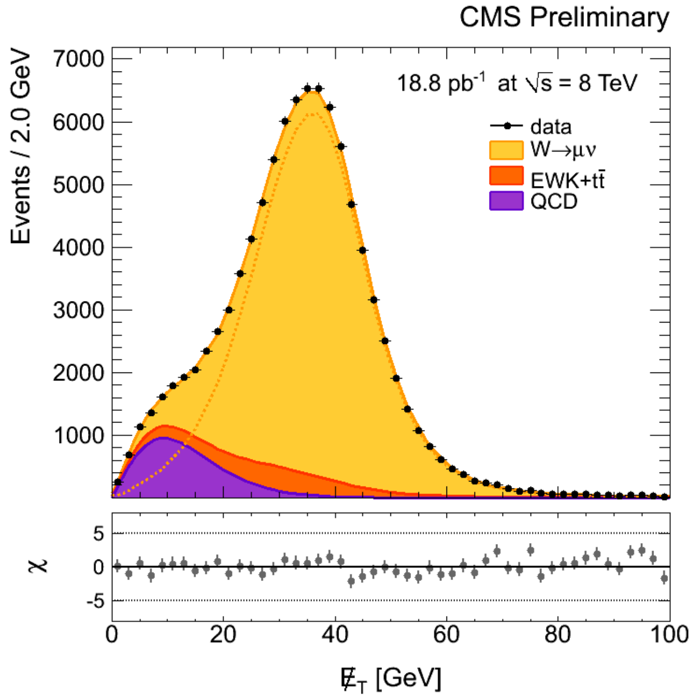


μ

Unbalanced transverse momentum = ‚ν'

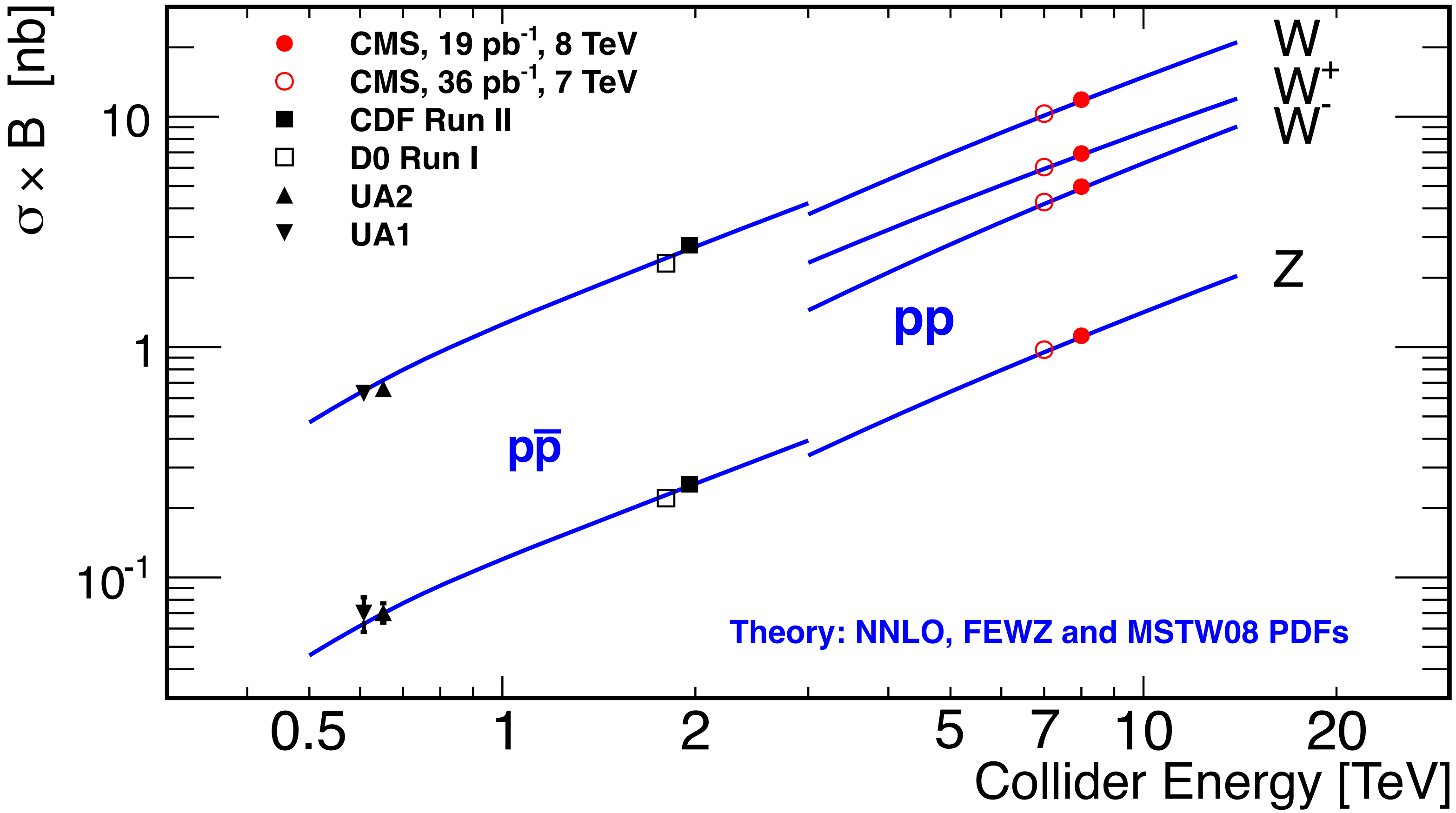
$$\mathrm{MET_x} = -\sum(\mathrm{p_x})_\mathrm{i}, \quad \mathrm{MET_y} = -\sum(\mathrm{p_y})_\mathrm{i}$$



Missing transverse momentum
not only due to ν
- mismeasurements
- additional jets/underlying ev.

Cross section ~ 10x higher than for Z^0

W/Z Cross section



Note different cross sections for W^+ and W^- at LHC

Theory in very good agreement with data

Production of W± Bosons

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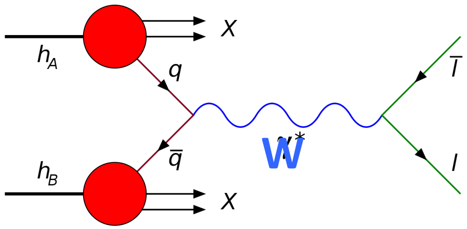


Drell – Yan process (leading order)

Very similar to Z – boson production
But different initial quarks (different flavour!!), e.g.

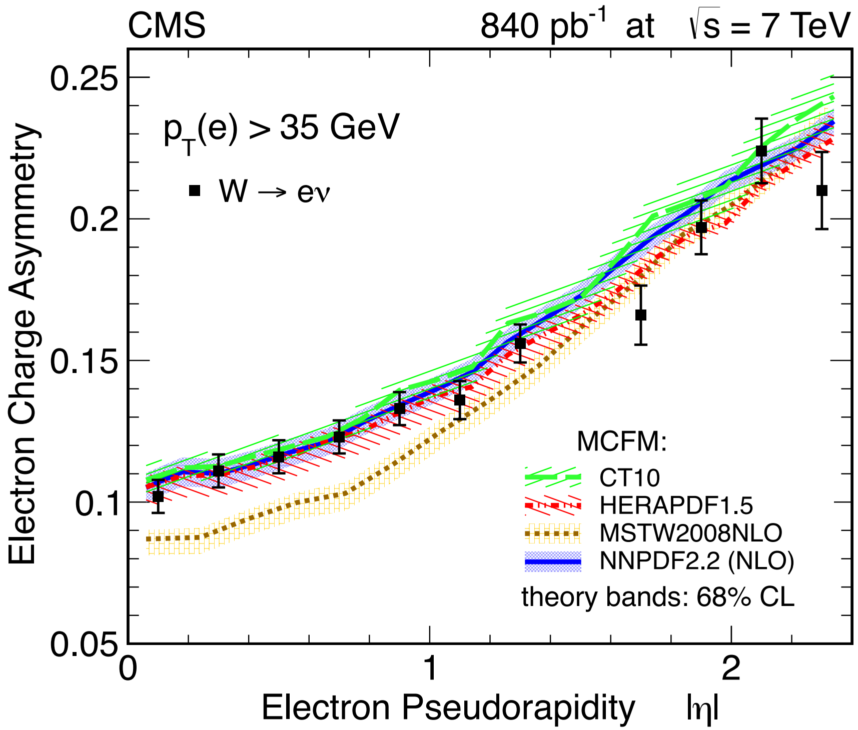
$$\mathbf{u\bar{d}} \rightarrow \mathbf{W}^+ \rightarrow \mu^+\bar{\nu}_\mu$$

$$\mathbf{\bar{u}d} \rightarrow \mathbf{W}^- \rightarrow \mu^-\nu_\mu$$

Sensitivity to different quark content in proton
➔ important calibration point for parton distribution function

W^+ vs. W^- production

$$A_\mu = \frac{N_{\mu^+}(|\eta|) - N_{\mu^-}(|\eta|)}{N_{\mu^+}(|\eta|) + N_{\mu^-}(|\eta|)}$$



LHC: pp – collider:

2 valence up quarks

1 valence down quark

➔ more W^+ than W^-

Sea quark **Valence quark**

Valence quarks have high x!

Sea quarks small x

➔ high η W - bosons

Note different predictions by pdfs

Comparing W/Z with pdfs

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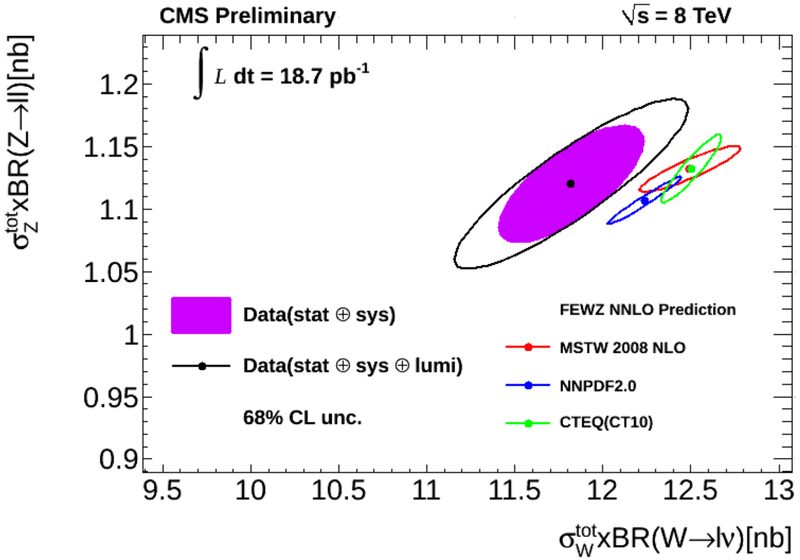
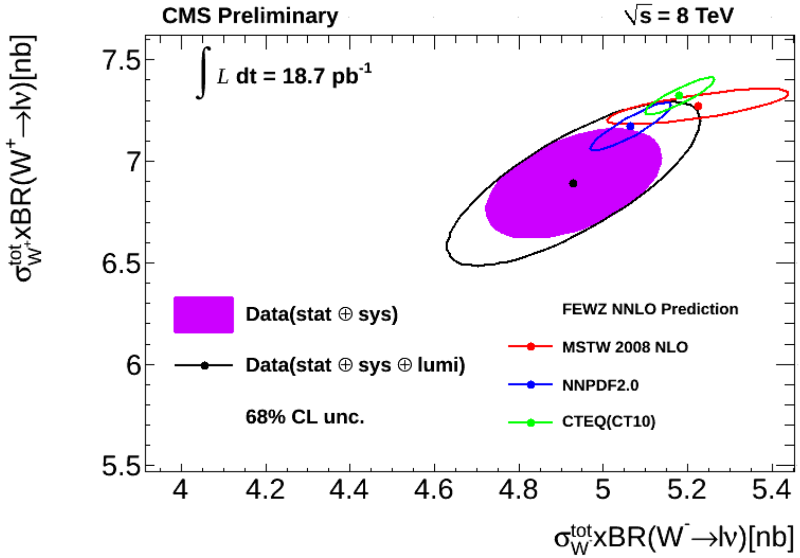
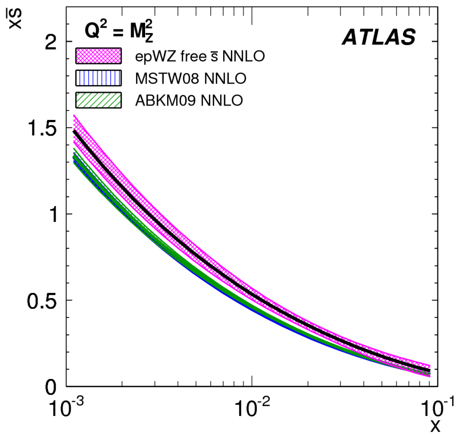


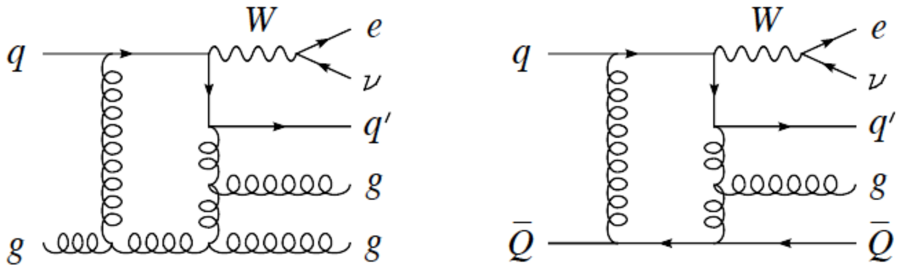


W & Z measurements significantly constrain pdfs for quarks

Using measurements on u, d
➔ Infer on strange component



W/Z + Jets



Example: W + 3 Jets

A QCD process theoretically quite well understood
Important background for many BSM/Higgs processes

- **Z & W + jets should have the same topology**
- **Simple minded approach**

$$\mathbf{R}(\mathbf{n}) = \frac{\sigma(\mathbf{V}+(\mathbf{n}+\mathbf{1})\text{ jets})}{\sigma(\mathbf{V}+\mathbf{n}\text{ jets})} = \alpha_{\mathbf{s}} = \text{constant}$$

‚Berends – Giele' scaling

Can be tested for the first time with high statistics up to many jets

W/Z + Jets

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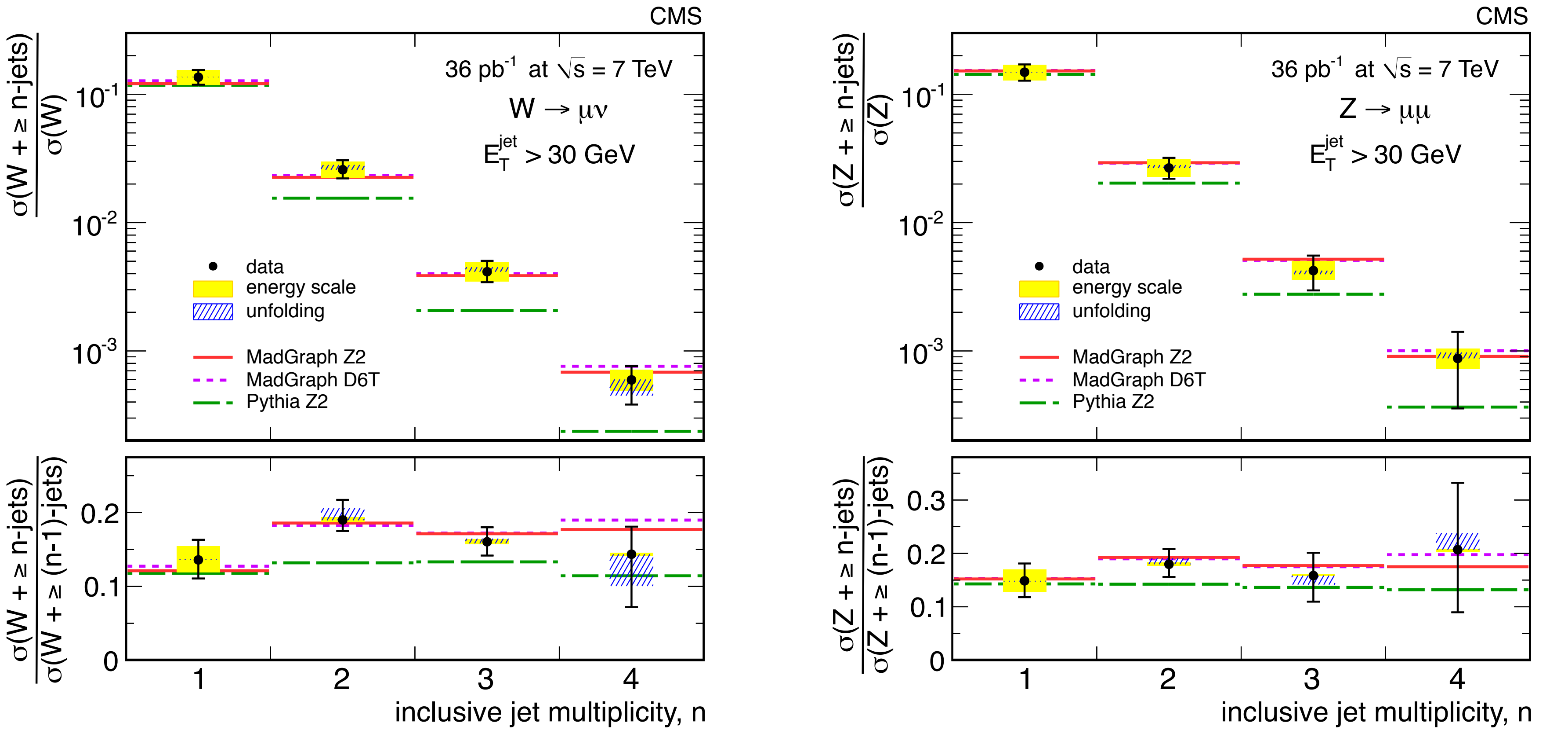
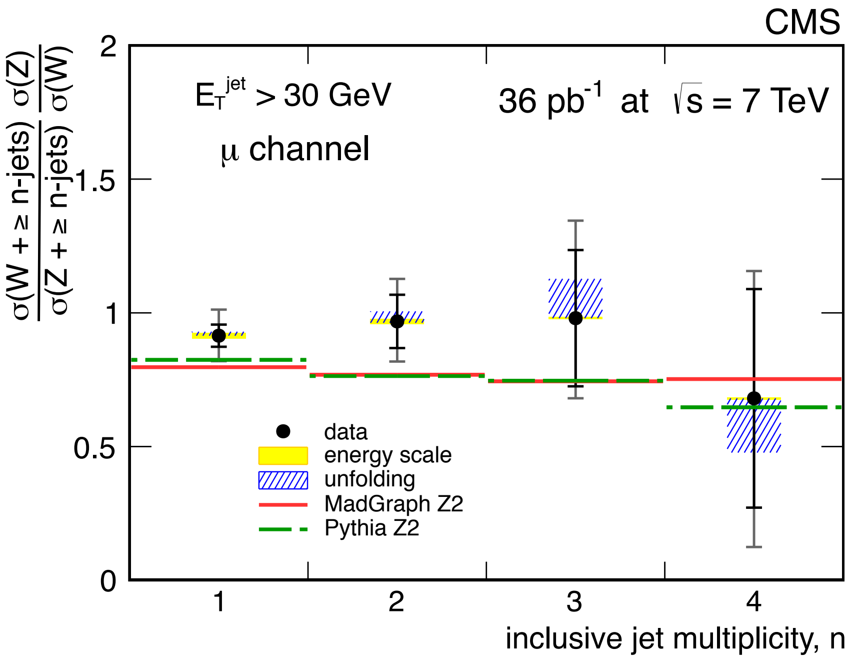
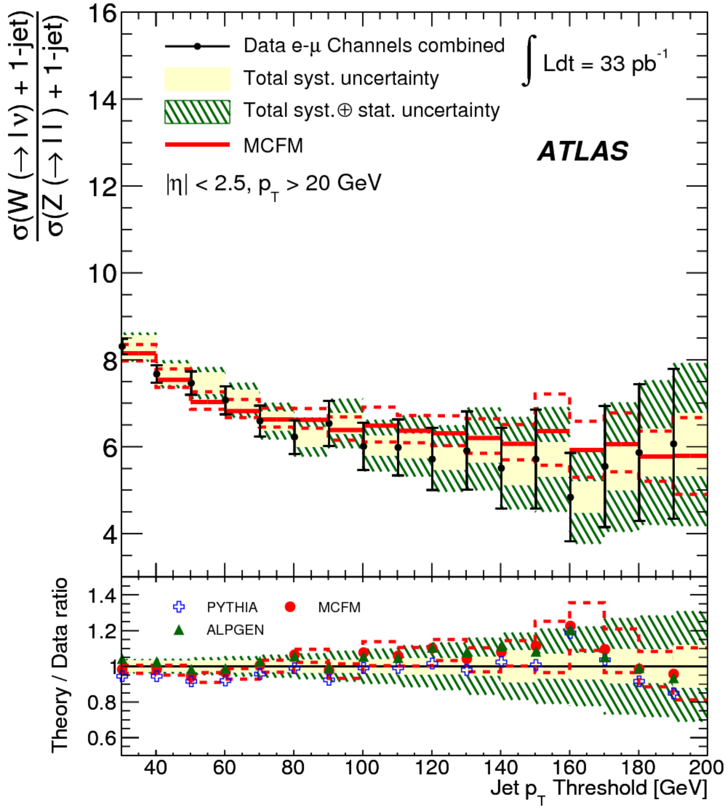


Test of Berends – Giele:

Fairly well confirmed, note model dependence

W/Z + Jets



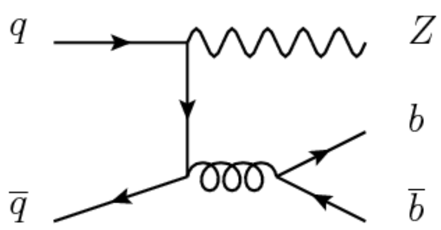


Z and W production fairly equal dependence in jet multiplicity

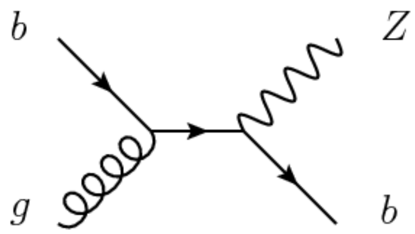
However, Z jets have harder p_T spectrum

Note: some deficiencies of simulation?

W/Z + bottom Jets



Similar for W/Z



Much larger Zbb cplg. than Wcb

The virtue of measuring these processes:

- understand background for processed like top pairs, V+H(bb)
- Potential for measuring (charm) + (bottom) pdf

CMS measurement (within cuts)

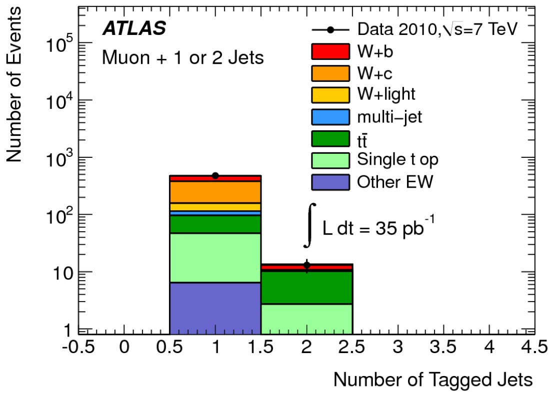
$\sigma(Z+b+X) = 5.84 \pm 0.08\ (\text{stat.}) \pm 0.72\ (\text{syst.})^{+0.25}_{-0.44}\ (\text{theory})\ \text{pb}$

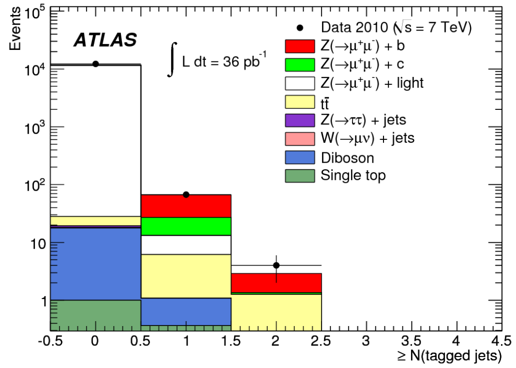
$\sigma(Z+bb+X) = 0.37 \pm 0.02\ (\text{stat.}) \pm 0.07\ (\text{syst.}) \pm 0.02 (\text{theory})\ \text{pb}$

Matrix element calculations in agreement

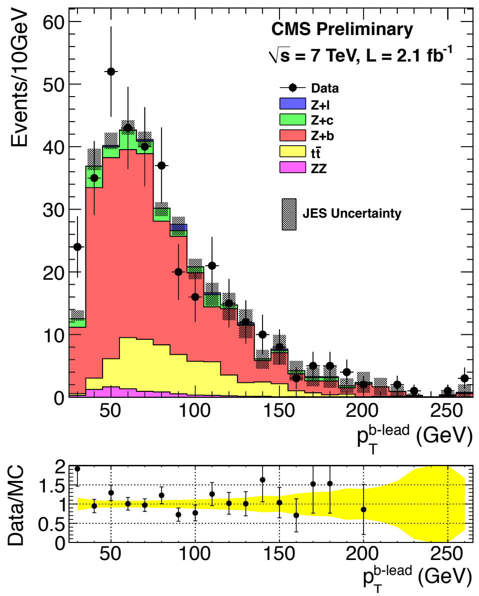
cp. Inclusive Z – production ~ 1 fb

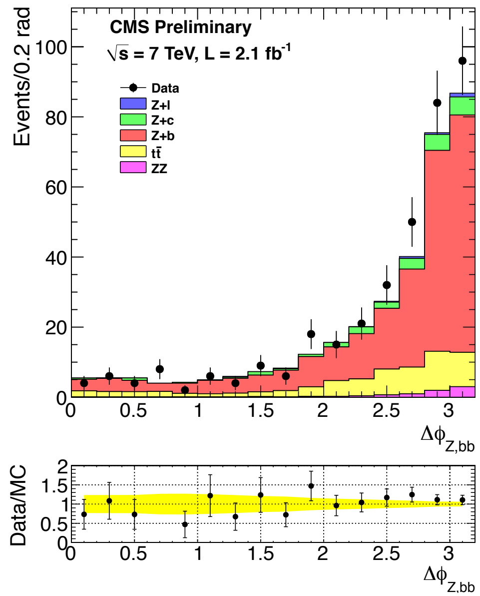
W vs. Z + bottom Jets





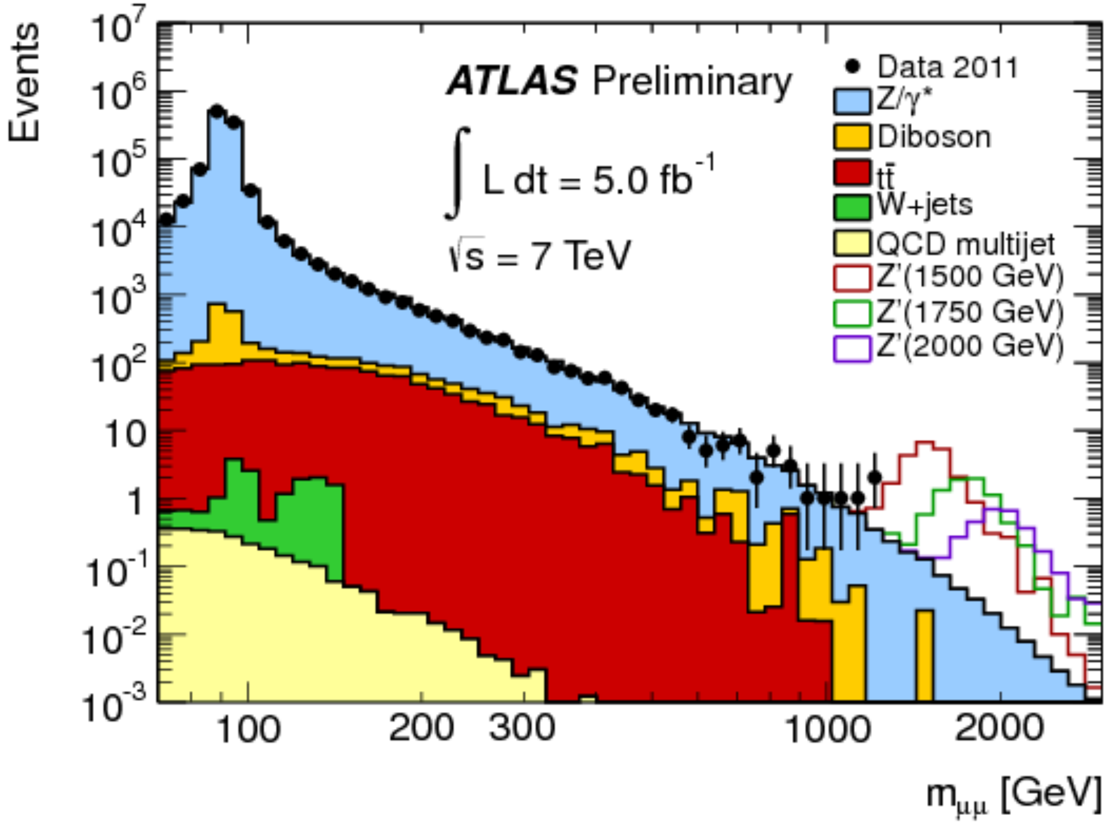
Fraction of bottom larger in Z^0 events





Properties of b – system in Z^0 events agree with expectation

Drell – Yan at TeV scale: ee, μμ

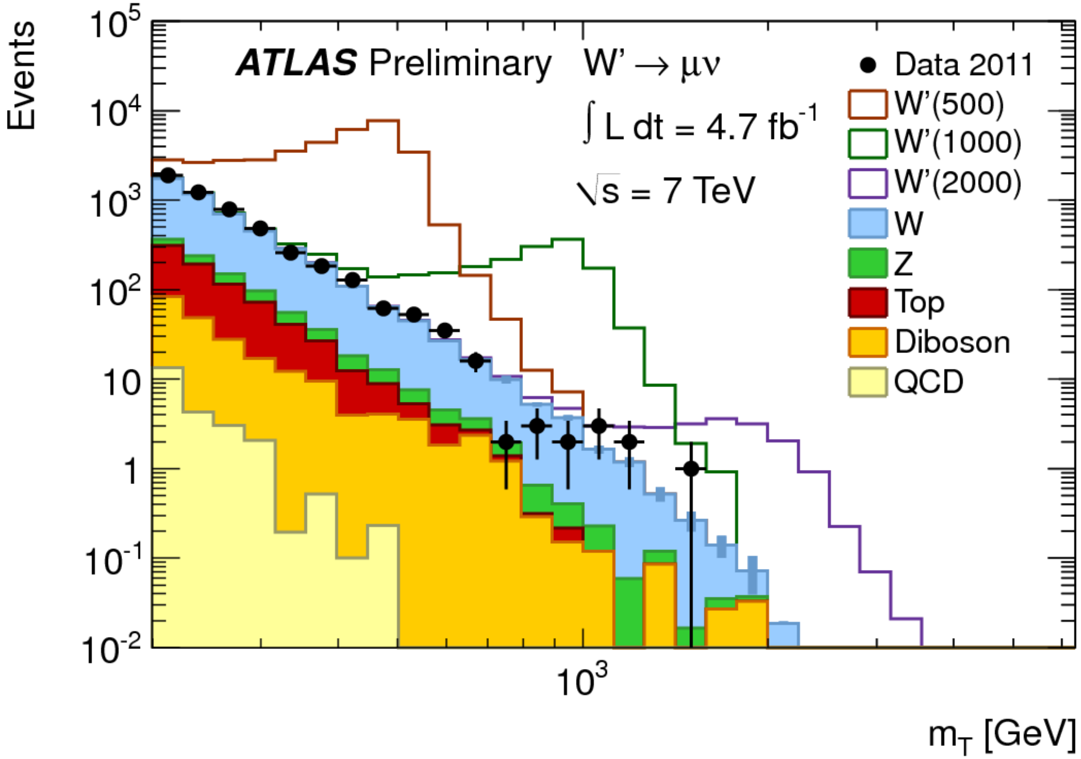


Search for deviations from Drell – Yan prediction

Many models predict ‚excited Z'

No resonance structure found:
$M_{Z'} > 2$ TeV (depending on model for new physics)

Drell – Yan at the TeV scale: $\mu\nu$



Search for deviations from Drell – Yan prediction

Many models predict ‚excited W'

No resonance structure found:
$M_{Z'}$ > 2.5 TeV (depending on model for new physics)

Standard Model @ Hadron Colliders
VII. Electroweak effects with W/Z

Polarisation of W

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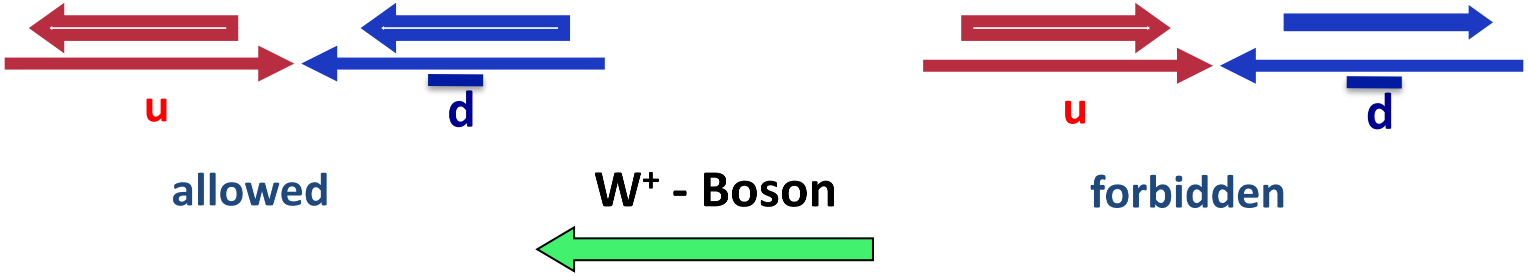
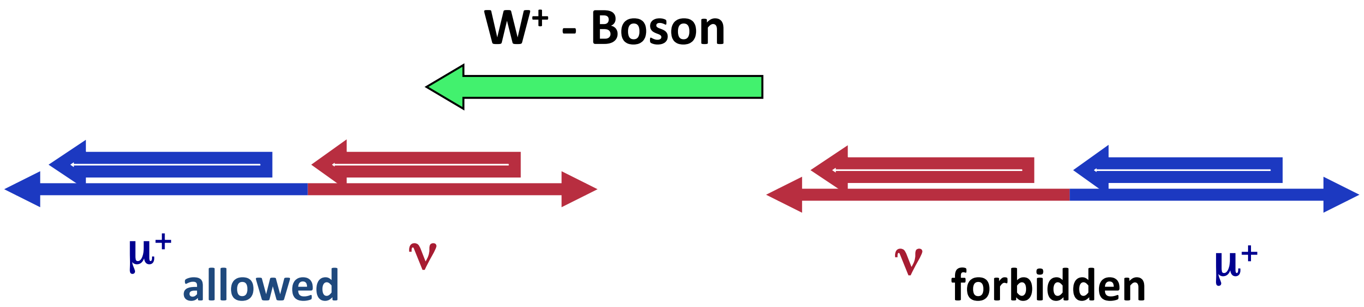
Production of W^+ - Boson



Decay of W^+ - Boson



At LHC

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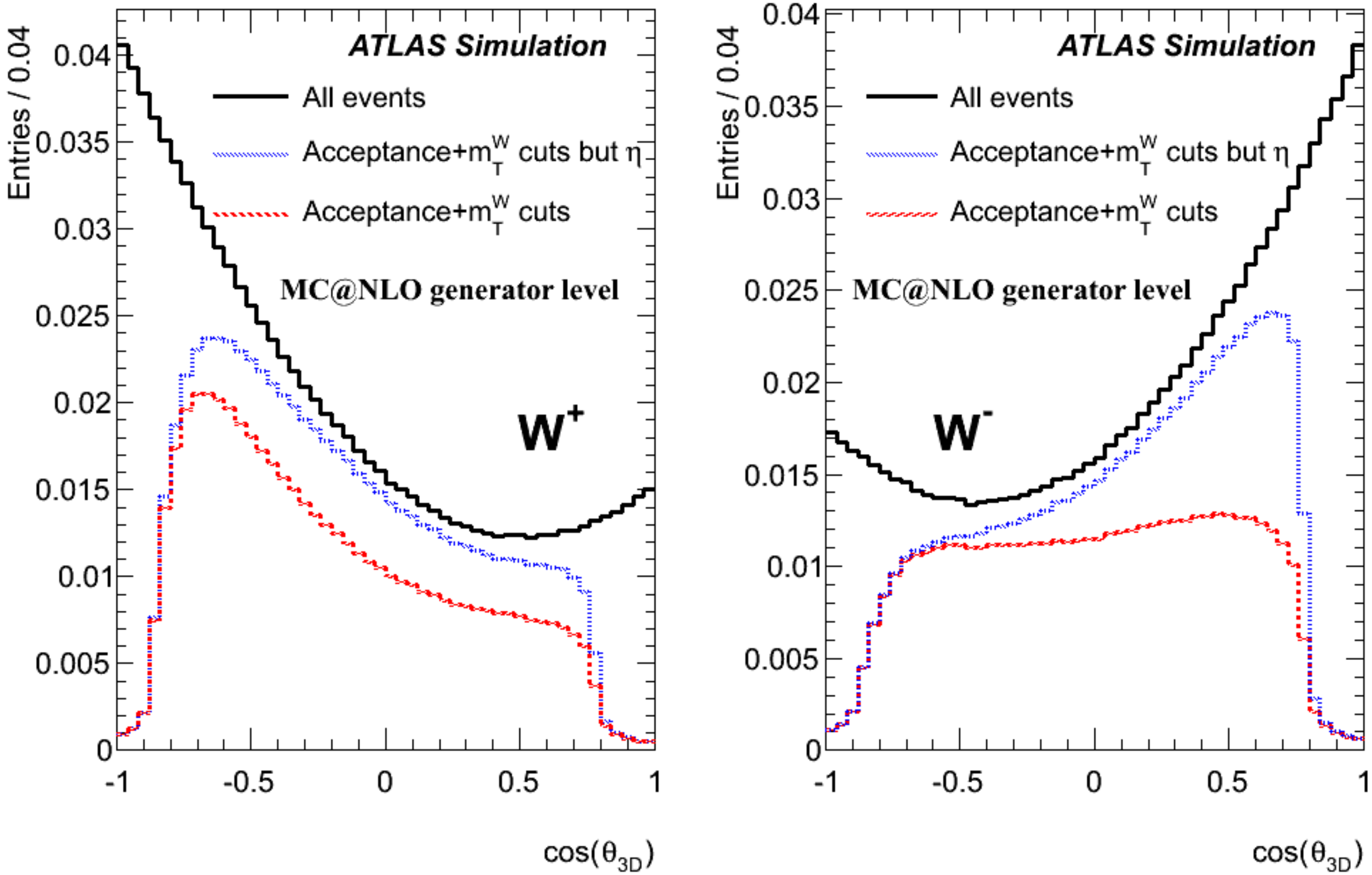
High y: u – quark valence quarks ➔ W Spin against flight direction
Central y: u – quark sea quarks ➔ Both W helicities

Additional modifications due to QCD effects ➔ high p_T also W_{Long}

$$\frac{d\sigma}{d(p_T^W)^2 dy_W \, d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^u}{d(p_T^W)^2 dy_W} \times \Big[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi\Big] \quad (1)$$

Detector effects



Polarisation of W

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